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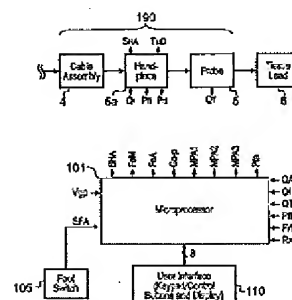
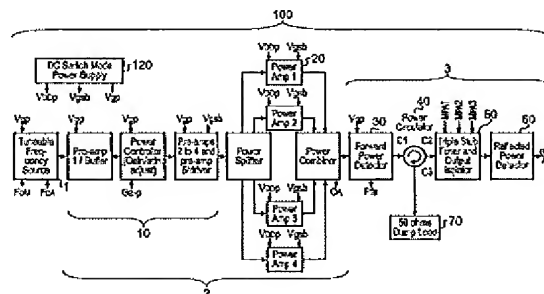
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(54) Title: TISSUE ABLATION APPARATUS AND METHOD OF ABLATING TISSUE



(57) Abstract: An apparatus and method for ablating tissue is disclosed. The apparatus comprises a source of microwave radiation (1), a probe (5) for directing the microwave radiation into tissue, one or more detectors for detecting the power and phase of the microwave radiation and an impedance adjuster (50) for adjusting impedance so as to minimize the amount of microwave radiation which reflected back through the probe. The detector or detectors use a local oscillator (230) to derive the phase information. A modulator for modulating the microwave radiation to a cutting frequency is also disclosed.

Tissue Ablating Apparatus and Method of Ablating TissueBACKGROUND TO THE INVENTIONFIELD OF THE INVENTION

5           The present invention relates to an apparatus and method for ablating tissue with microwave radiation. In this specification microwave means the frequency range from 5GHz to 60GHz inclusive. Preferably 14-15GHz is used for tissue ablation but the present invention is not  
10           limited to this narrower range.

SUMMARY OF THE PRIOR ART

          Traditional methods of treating cancer involve removing the cancerous tissue by cutting it out  
15           mechanically and/or chemotherapy, usually followed by radiotherapy. Both methods have significant drawbacks and may cause serious trauma to the patient.

          The application of heat energy to biological tissue  
20           is an effective method of killing cells. Thus the present invention proposes applying microwaves to heat and thus ablate (destroy) biological tissue. This presents an interesting opportunity for the treatment of cancer as the cancerous tissue can be ablated in this way. There is  
25           a need for a suitable apparatus and method for ablating tissue with microwaves for the treatment of cancer or other conditions.

SUMMARY OF THE INVENTION

30           Accordingly a first aspect of the present invention may provide a tissue ablation apparatus comprising:  
          a source of microwave radiation;

a probe for directing the microwave radiation into the tissue to be ablated;

a local oscillator for producing a signal having a different frequency to said microwave radiation;

5 a first detector for detecting the magnitude and phase of microwave radiation reflected back through the probe towards the source, said first detector being connected to said local oscillator, and

10 an impedance adjuster having an adjustable complex impedance, between said source and said probe.

In this specification except where the context demands otherwise, the term 'connected' includes not only direct connection but also indirect connection via one or  
15 more intermediate components.

The tissue ablation apparatus may comprise:

a source of microwave radiation having a frequency;  
a probe connected to said source, said probe being  
20 configured for directing said microwave radiation into said tissue to be ablated;

a local oscillator for producing a signal, having a frequency different to said frequency of said microwave radiation;

25 a first detector for detecting the magnitude and phase of a reflected portion of said microwave radiation reflected back through said probe towards said source;

said first detector being configured to determine the magnitude and phase of said reflected portion of said  
30 microwave radiation on the basis of said signal produced by said local oscillator and said reflected radiation, and

an impedance adjuster having an input connected to said source of microwave radiation and an output connected to said probe, said input and output having respective complex impedances, said complex impedance of said output being adjustable.

As said adjustable complex impedance of the impedance adjuster can be adjusted, the amount of reflected radiation can be minimised, thus improving the efficiency of the energy delivery to the tissue.

In general the level of radiation reflected back through the probe by a load (e.g. tissue) at the distal end of the probe will be minimised if the impedance at the output of the impedance adjuster is matched with the impedance of the load (e.g. the tissue being ablated).

A channelling means such as a coaxial cable or a waveguide may be used to connect the impedance adjuster to the probe. If the distance travelled by the microwave radiation between the output of the impedance adjuster and the distal end of the probe is equal to a multiple of  $\lambda/2$  (where  $\lambda$  is the wavelength of the radiation), then it is a simple matter of matching the output impedance of the impedance adjuster to the impedance of the load (e.g. tissue) at the distal end of the probe. Otherwise the impedance can still be matched to minimise reflections, but the impedances of the probe and the channelling means also need to be taken into account (so e.g. the output impedance of the impedance adjuster needs to be matched to the combined impedance of the load, the channelling means and the probe). Therefore it is preferable, but

not essential for said channelling means to have an adjustable length whereby the combined length of said channelling means and said probe can be adjusted to be equal to a multiple of  $\lambda/2$ .

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If the detector only provided magnitude (i.e. amplitude or power) information then it would not be possible to adjust the complex impedance quickly enough to effectively minimise the reflected radiation. Another advantage of using phase information is that phase differences can be measured even when the signal to noise ratio is poor. Therefore the detector has to provide both magnitude and phase information. In order to provide phase information it is necessary to have a local oscillator, providing a signal having a frequency different to the frequency of microwave radiation, so that the phase of the detected microwave radiation can be compared with that of the signal from the local oscillator.

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Usually the detector will comprise a mixer for mixing the signal from the local oscillator with the microwave radiation. For example the detector may detect the reflected magnitude and phase by heterodyne detection (mixing of the reflected radiation or a signal derived from it with the signal from the local oscillator). Alternatively the phase can be detected by a phase comparator configured to compare the phase of the reflected microwave radiation with that of the local oscillator signal. The reflected microwave radiation may be passed through one or more frequency transformers before entering the mixer or the phase comparator, this

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is particularly helpful if a phase comparator is used because phase comparators tend to work more accurately at lower frequencies.

5            Preferably the apparatus further comprises a second detector for detecting the magnitude and phase of forward directed microwave radiation (radiation directed from said source toward said probe).

10            As for the first detector above, it is necessary to have a local oscillator so that the phase of the microwave radiation can be determined. Preferably the same local oscillator as for the first detector is used. So, for example if the detectors use mixers, then each  
15            detector will have its own mixer and both mixers will be connected to a common local oscillator. In such a case the output from the local oscillator may need to be buffered in order to drive two or more mixers. Alternatively each mixer could be connected to a  
20            different local oscillator, but that would make it harder to detect the phases and make the appropriate impedance adjustments, because of differences between the local oscillator signals.

25            The presence of a second detector for detecting the magnitude and phase of 'forward directed' microwave radiation makes it easier to determine the appropriate impedance adjustment. If there is only one detector then more assumptions need to be made about the  
30            characteristics of the apparatus (e.g. the phase change caused by the apparatus between the input to the impedance adjuster and the probe/tissue interface).

Preferably there is also a third detector. The third detector is either configured to detect the magnitude and phase of reflected microwave radiation or it is configured to detect the magnitude and phase of 'forward directed' microwave radiation. The third detector enables the appropriate (complex) impedance adjustment to be determined more accurately. When there is a third detector it is possible to monitor the change in complex impedance due to adjustments of the impedance adjuster itself. It may also be possible to directly determine the phase difference between the input and output of the impedance adjuster which information is useful in determining the appropriate adjustment to be made.

As for the second detector, the third detector needs to be connected to a local oscillator. This may be the same local oscillator as for one or both of the first and second detectors, or a different one. Preferably all the detectors share a common local oscillator, again possibly will buffering.

Where a phase comparator is used, the first, and (if present) second and third detectors can be combined into one unit.

The or each local oscillator may be separate and independent from the source of microwave radiation.

Alternatively the or each local oscillator may produce a signal derived from said source of microwave

radiation, but having a different frequency. Typically this is done by a frequency transformer which transforms a signal from said source of microwave radiation down to a lower frequency. This lower frequency 'local  
5 oscillator' signal can then be input into a mixer of the detector for mixing the forward directed or reflected microwave radiation or used as a reference signal for a phase comparator. In effect the frequency transformer, connected to the source of microwave radiation acts as  
10 the local oscillator.

Another approach is to have a separate local oscillator, but to mix the local oscillator signal with a signal from said source of microwave radiation and to  
15 input the result of this mixing to the detector. Typically, a filter will be provided between the mixer and the detector itself (which may itself comprise a mixer as noted above) to filter out any unwanted frequencies.

20 The impedance adjuster may be operated by a human operator in response to data relating to the detected magnitude and phase displayed on a display. Preferably however, said adjustable complex impedance of the  
25 impedance adjuster is adjusted automatically by a controller on the basis of the magnitude and phase of the radiation detected by said detector(s). The controller may for example take the form of an integrated circuit or a computer.

30 Preferably the controller is configured to adjust said adjustable complex impedance dynamically (in real time) in response to the variation in the magnitude and



phase of the radiation detected by said detector(s). In this way the impedance can be adjusted as the characteristics of the tissue change during the ablation process. For effective dynamic control the adjustment  
5 time would be less than the relaxation time (or response time) of the tissue.

The impedance adjuster may take any suitable form. For example it could be a semiconductor device or a stub  
10 tuner. In the case of a stub tuner, the tuner may have one, two, three or more stubs. A three-stub tuner is preferred as this can adopt a wide range of complex impedances (in theory any impedance on the Smith chart). Another possibility is to have an impedance adjuster  
15 comprising a phase adjuster and a magnitude adjuster (e.g. two variable length lines or a variable length line and a tuning stub; the variable length line(s) may be coaxial or striplines).

20 There may be provided electrically activateable actuators for controlling the impedance adjuster. If a stub tuner is used as the impedance adjuster then the electrically activateable actuator(s) may, for example, be one or more piezoelectric devices or servo-motors for  
25 controlling the stub(s) to adjust the impedance. The actuator(s) may be controlled by said controller, so that the control of the impedance matching is automatic.

30 Preferably the source of microwave radiation is a stable single frequency source, for example a phase locked source or a broadband source with a narrow band filter. This is helpful when detecting phase changes,

e.g. in the reflected microwave radiation. The source may be a VCO (Voltage Controlled Oscillator) or a DRO (Dielectric Resonator Oscillator); other possible sources will be apparent to a person skilled in the art. The  
5 source may be tuneable so that the frequency can be varied in a controlled manner.

The probe can be coaxial or a waveguide (which may be loaded or unloaded).

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Preferably the probe is configured to penetrate biological tissue. For example it may have a pointed end. This enables the probe to be inserted into the tissue until it is close to or inside a tumour, which is to be  
15 ablated. The microwaves can then be effectively directed at the tumour. It is particularly advantageous to have a probe that is capable of being inserted by key-hole surgery. Accordingly the probe preferably has an outer diameter of less than 1mm. This small size minimises  
20 trauma to the patient and also increases the energy density of the microwave radiation exiting the probe.

The probe may be a coaxial probe - having a central conductor, an outer conductor and a dielectric between  
25 said two conductors. There may also be one or more baluns (balanced to unbalanced transformers) on the outer conductor to minimise the return current on the outer conductor (which current may cause shock to the patient or the person operating the apparatus). The baluns may  
30 take the form of a ring or sheath of conducting material surrounding the outer conductor. Dielectric baluns can also be used.

Preferably the apparatus has a separator for separating the reflected microwave radiation from the 'incident' (forward directed) microwave radiation being  
5 directed out of the probe. This separator may for example take the form of a circulator. Alternatively it could be a power 3dB coupler.

Preferably the apparatus has a first coupler for  
10 directing some of the reflected radiation to the first detector. Any suitable coupler may be used, e.g. a single port coupler, however a six port coupler may be advantageous. There may also be a second coupler for directing some of the outgoing (forward directed)  
15 radiation to a second detector. There may be a third coupler for directing radiation to a third detector; said third coupler will either be a reflected radiation coupler or a forward directed radiation coupler. Preferably said couplers are highly directional to ensure  
20 good differentiation between forward and reflected radiation.

At its most general a method according to the present invention comprises the step of placing a probe  
25 in contact with biological tissue and delivering microwave radiation through said probe to said tissue to ablate at least a portion of said tissue. Preferably the method is used to treat cancer. The tissue may have a cancerous portion, or tumour, in which case the radiation  
30 is used to ablate said cancerous portion or tumour, preferably leaving the surrounding non-cancerous tissue substantially unharmed.

Very fine (diameter less than 1mm) probes will be advantageous in some procedures, but the present invention is not limited to these.

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It is thought that the present invention will be especially useful in treating breast cancer. Treatment of brain tumours is another possible application. However the present invention is not limited to these applications. It may also be used to treat lung cancer, liver cancer (e.g. liver metastases), prostate cancer, skin cancer, colo-rectal carcinoma, or any carcinoma where solid tumours are present and can be ablated. Other applications will be apparent to a person skilled in the art. In some embodiments the present invention may be useful for treating conditions other than cancer, for example skin disease or brain disease (especially, but not exclusively in regions near the optic nerve).

Thus, a second aspect of the present invention may provide a method of ablating tissue comprising the steps of:

using a source of microwave radiation to provide microwave radiation;

placing a probe in contact with or inserting a probe into biological tissue;

directing said microwave radiation through said probe into the tissue to ablate the tissue;

detecting the magnitude and phase of microwave radiation reflected back through the probe by using a first detector and a local oscillator, and

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adjusting the complex impedance of an impedance adjustor between said source and said probe on the basis of the magnitude and phase of the microwave radiation detected by said first detector.

5

The method may comprise the steps of:

using a source of microwave radiation to provide microwave radiation having a frequency;

placing a probe in contact with or inserting a probe into biological tissue;

directing said microwave radiation from said source through an impedance adjuster and then through said probe into said tissue to ablate the tissue; said impedance adjustor having an input connected to said source and an output connected to said probe, said input and said output having respective complex impedances;

detecting the magnitude and phase of reflected microwave radiation reflected back through the probe by using a first detector and a local oscillator; said local oscillator generating a signal having a frequency different to said frequency of said microwave radiation, said first detector using said local oscillator signal in combination with the reflected radiation or a signal derived from said reflected radiation to determine the magnitude and phase of said reflected radiation;

and adjusting said complex impedance of said output of said impedance adjustor on the basis of said magnitude and phase of said reflected microwave radiation detected by said first detector, so as to minimise the amount of microwave radiation which is reflected back through said probe.

Preferably this method is a method of treating cancer using the apparatus of the first aspect of the present invention.

5            Preferably the probe is inserted into the tissue until an end of the probe is proximate to or preferably inside a cancerous tumour in the tissue and microwave radiation is then passed through the probe to ablate said cancerous tumour.

10           Preferably microwave radiation from the probe is used to cut a path in the tissue so that the probe can be inserted near to or into the tumour. This is an effective method of getting the probe close to or into the tumour.

15           Preferably the microwave radiation from the probe is used to seal the path of the probe on exiting the tissue and/or the body being treated.

20           Preferably the magnitude and phase of forward directed microwave radiation directed into said probe from said source of microwave radiation is detected by a second detector and a local oscillator and said adjustable complex impedance of said impedance adjuster  
25           is adjusted based on the magnitudes and phases detected by said first and second detectors, e.g. on the basis of the phase and magnitude difference between the forward directed and reflected radiation.

30           Preferably a third detector is used to detect the magnitude and phase of either forward directed or reflected radiation and said adjustable complex impedance of said impedance adjuster is adjusted on the basis of

information provided by said first, second and third detectors, e.g. on the basis of the magnitude and phase differences between the detectors.

5            Preferably said adjustable complex impedance of the impedance adjuster is adjusted automatically by a controller on the basis of the magnitude and phase detected by said detectors so as to minimise the amount of radiation reflected back through said probe.

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            Preferably the impedance adjustment is carried out dynamically (in real time) as the detected magnitude and phase varies. This enables said adjustable complex impedance of the impedance adjuster to be adjusted as the impedance of the tissue changes during the ablation process. This minimises probe and cable heating (caused by reflected energy in the apparatus for long period of time), and may help to provide a fast, efficient controlled ablation process.

20

            Further preferred features may be found in the claims.

25            A third aspect of the present invention provides an elongate microwave probe for delivering microwave radiation into tissue to be ablated, said probe having an elongate portion and a tip at one end of said elongate portion, said tip being formed of a ceramic material and being configured to deliver microwave radiation into  
30            tissue.

Ceramic material is suitable for the tip; because ceramics are relatively hard, can have a high permittivity ( $\epsilon_r$ ) which helps to focus EM fields and a good thermal conductivity which reduces heating of the tip.

Preferably the tip is cone or dome shaped. This helps to focus microwaves leaving the probe.

Preferably the ceramic is a microwave ceramic. For example microwave ceramics from Pacific Ceramics Inc., could be used.

Preferably the microwave ceramic has a permittivity greater than unity, more preferably from  $\epsilon_r = 6.5$  to  $\epsilon_r = 270$  at microwave frequencies. Preferably the microwave ceramic has low loss ( $\tan \delta$ ) at the microwave frequencies of interest.

A fourth aspect of the present invention provides a coaxial tissue ablation probe having an inner conductor, a dielectric surrounding said inner conductor, a conducting sheath surrounding said dielectric and one or more baluns on said sheath, the or each balun comprising a spray-on dielectric. Preferably the or each balun also comprises an outer conductor surrounding said spray-on dielectric. As the dielectric is a spray-on dielectric it is possible to make the baluns very small. This is necessary where the probe is of small cross-section and/or the frequencies high.



According to a fifth aspect of the present invention there is provided a method of making a balun for a coaxial tissue ablation probe comprising the steps of spraying or otherwise placing a liquid or powder  
5 dielectric onto an outer surface of an outer conducting sheath of a coaxial probe, if said dielectric is liquid allowing the liquid to solidify, to form the balun.

In both the fourth and fifth aspects of the present invention, preferably said probe is designed for use with  
10 a microwave radiation of wavelength  $\lambda$  and the balun has a length in the direction of the axis of said probe approximately equal to  $\lambda/4$  or odd multiples thereof.

15 A sixth aspect of the present invention provides a surgical apparatus comprising:

a source of microwave radiation of a first frequency suitable for ablating tissue;  
20 a probe for directing microwave radiation from the source into tissue to be ablated;  
a modulator having an OFF state in which it does not modulate said microwave radiation from the source and an ON state in which it modulates microwave radiation  
25 from the source in pulses having a second frequency less than said first frequency; said second frequency being suitable for cutting tissue. Thus the probe can output two different frequencies - one optimised for tissue ablation (e.g. for ablating cancerous tissue), the other  
30 for tissue cutting (e.g. through healthy tissue to get to the cancerous tissue) - but the apparatus only needs one

source of radiation. This is better than having two separate radiation sources.

5 Preferably the first frequency, for tissue ablation, is 1GHz or higher, more preferably 13GHz or higher. In one embodiment it is in the range 14-15GHz.

10 The second frequency, for tissue cutting, is preferably in the range of 10kHz to 500 MHz. These frequencies have been found to be efficient at tissue cutting. More preferably the range to 500kHz to 30MHz.

15 Preferably the apparatus further comprises a low pass filter between said modulator and said probe; said low pass filter having a first state in which it lets said first frequency pass and a second state in which it passes said second frequency, but filters out said first frequency. The apparatus works without the filter, but the filter improves the cutting effect of the second frequency.

20 Preferably said modulator is capable of varying said second frequency.

25 Preferably said low pass filter is capable of varying its pass band in its second state when the modulator frequency is varied. This makes the apparatus more flexible.

30 Any of the features of the first to sixth aspects of the present invention described above may be combined with each other.

BRIEF DESCRIPTION OF THE DRAWINGS

5           Embodiments of the present invention will now be described with reference to the accompanying drawings in which:

          Fig. 1 is a block diagram of a tissue ablation apparatus that uses microwaves;

10           Fig. 2 is a schematic diagram showing the forward power detector, reflected power detector and circulator of the apparatus of Fig. 1 in more detail;

          Fig. 3 is a diagram of part of a power amplifier stage in the apparatus of Fig. 1 for amplifying  
15 microwaves produced by the microwave source;

          Fig. 4 is a diagram of an alternative power amplifier stage;

          Fig. 5 is a diagram showing the source of microwave radiation and a pre-amplifier stage in the apparatus of  
20 Fig. 1;

          Fig. 6 shows an alternative source and pre-amplifier stage arrangement;

          Fig. 7 shows an impedance adjuster;

          Fig. 8 is a cross sectional view of the impedance  
25 adjuster of Fig. 7 along the line A-A of Fig. 7;

          Fig. 9 shows a coaxial probe being inserted into some tissue;

          Fig. 10 is a cross-sectional view of the coaxial probe of Fig. 9 along the line B-B;

30           Figs. 11a-11e show different types of possible end structures for the probe;

          Fig. 12 shows a coaxial probe inserted into tissue;

Fig. 13 is a cross-sectional view along the line C-C of Fig. 12;

Fig. 14 shows a coaxial probe having baluns formed by a particular technique;

5 Fig. 15 shows a probe in the form of a rectangular waveguide;

Fig. 16 shows an alternative embodiment of the apparatus in which a signal from a local oscillator is combined with a signal from the source of microwave  
10 radiation;

Fig. 17 shows a configuration in which the local oscillator signal is derived from the signal provided by the source of microwave radiation;

Fig. 18 shows an alternative detection arrangement  
15 using a phase comparator;

Fig. 19 shows a phase locked source;

Fig. 20 shows a broadband source combined with a narrow band filter;

Fig. 21 shows an alternative embodiment having a  
20 modulator, and

Fig. 22 shows a probe in the form of a cylindrical waveguide, and

Fig. 23 shows a probe with a ceramic tip.

## 25 DETAILED DESCRIPTION OF THE INVENTION

### Overview of the Apparatus

A block diagram of an apparatus for ablating tissue with microwaves is shown in Fig. 1. The apparatus has a  
30 unit 100 for generating and controlling the microwave radiation and grouped generally under reference numeral 190 a probe 5 and a channelling means 4 for delivering

the microwave radiation to the probe. The probe 5 can be used to apply the microwave radiation to tissue 6 in order to ablate the tissue.

5           As the tissue 6 may reflect some of the microwaves back into the probe 5 and the unit 100, it is necessary to have a way of impedance matching the apparatus 100, 200 to the tissue 6. This is provided by components generally grouped under reference number 3 for monitoring  
10 the reflected microwaves and adjusting the impedance accordingly. This important part 3 of the apparatus takes into account both the magnitude and phase of the reflected microwaves. In the present embodiment it is provided as a sub-unit in the unit 100. It is described  
15 in more detail later.

          The unit 100 comprises a source of microwave radiation 1, an amplifying system 2 for amplifying microwaves from the source 1, components 3 for detecting  
20 microwaves and adjusting impedance, a power supply 120 and a controller 101 for controlling the amplifying system 2 and the unit 3 accordingly.

          The unit 100 is connected to the probe 5 by  
25 channelling means 4 and a holder 5a. The channelling means 4 may take any form suitable for channelling microwaves, for example a waveguide or a coaxial cable. It is advantageous if the channelling means 4 and the probe have a combined length equal to a multiple of  $\lambda/2$   
30 (where  $\lambda$  is the wavelength of the microwave radiation generated by the source 1), because this makes the channelling means 4 and the probes transparent to the

microwave radiation, so that their impedances can be ignored when impedance matching the tissue 6 to the apparatus 100, 200. This makes impedance matching easier. Accordingly there may be length adjuster so that the effective length of the channelling means can be adjusted. Possible length adjusters include a telescopic connector, a coaxial trombone phase adjuster or a pin diode phase adjuster. The impedance matching is discussed in more detail later.

The microwave amplifying system 2 has a pre-amplifier 10 and a power amplifier 20, both of which are described in more detail later.

The unit 3 has a first detector 60 for detecting the magnitude and phase of microwaves reflected back into the apparatus (reflected microwave radiation) and a second detector 30 for detecting the magnitude and phase of the microwaves being directed towards and through the probe 5 ('forward directed microwave radiation'). These two types of microwave radiation are discriminated by their direction and so the detectors may be termed forward 30 and reverse (or reflected radiation) 60 detectors respectively.

The unit 3 has a circulator 40 for separating microwaves travelling to the probe from microwaves reflected back into the probe (e.g. microwaves reflected by the tissue 6). While the detectors are preferably designed to be capable of discriminating the forward and reflected microwaves, it is highly preferable to have a circulator 40 as well for the following reason. The

circulator 40 acts as an isolator for preventing reflected radiation being directed back into the amplifying system 2, which could damage the amplifiers.

5           The circulator 40 has three ports C1, C2 and C3 connecting it to the surrounding circuitry. Port C1 connects it to the source 1 via the forward detector 30 and the amplifying system 2, port C2 connects it to the probe via the impedance adjuster 50, the reverse detector  
10       60 and the channelling means 4, and port C3 connects it to a dump load 70. Radiation entering at C1 exits the circulator at C2 and reflected radiation entering the circulator at C2 exits the circulator at C3. A power yttrium iron garnet (YIG) circulator may be used.

15

#### Detectors

As mentioned above the detectors 30, 60 detect both the magnitude and phase of the microwave radiation. Fig.  
20       2 is a schematic diagram showing the unit 3 and in particular the detectors 30, 60 in more detail. The first power detector 60 for detecting the magnitude and phase of microwave radiation reflected back through the probe comprises a directional coupler 200 connected to the  
25       impedance adjuster 50 which is connected to port C2 of the circulator. The directional coupler 200 directs a portion of the reflected radiation to mixer 220 where it is mixed with a signal from a local oscillator 230.

30

This mixing produces an intermediate frequency signal that is detected by detecting device 240, connected to an output of said mixer 220, so that both

the magnitude and phase of the reflected radiation can be derived. In other words the system is a heterodyne detection system. There may be a filter (not shown) between the detecting device 240 and the mixer 220 to  
5 filter out unwanted frequencies produced by mixing. The magnitude and phase information is sent to the controller 101. In alternative embodiments the function of the device 240 may be carried out by the controller itself. In such a system, it is preferable that the intermediate  
10 frequency is generated on the difference between the frequency of the signal from the local oscillator and the frequency of the reflected radiation. However, it is also possible for the intermediate frequency to be the source of the frequency of the signal from the local  
15 oscillator and the frequency of the reflected radiation.

It is necessary to have the local oscillator 230 so that the phase as well as the magnitude can be detected. In other embodiments the reflected radiation may be  
20 passed through frequency transformers and/or other devices between the directional coupler 200 and the mixer 220 to make it easier to handle before it is mixed with the signal from the local oscillator.

25 The second detector 30 comprises a directional coupler 250 which couples the majority of incoming radiation to port C1 of the power circulator 40, but directs a portion to a second mixer 260 connected to said local oscillator 230 and a detecting device 280 arranged  
30 in the same manner as described above for the first detector 60.



In an alternative embodiment it would be possible for the first and second detector 30, 60 to be connected to different local oscillators, rather than one common oscillator 230 as shown in Fig. 2.

5

It will be appreciated to those skilled in the art that the components need not be in the order shown in Figs. 1 and 2. For example the detectors and impedance adjuster 3 could be at the end of the channelling means 4  
10 between the channelling means 4 and the probe 5. It would also be possible to separate the components and/or rearrange their order. For example, the forward coupler 250 could be placed between the circulator 40 and the impedance adjuster 50 or even between the circulator 40  
15 and the dump load 210. It would also be possible to have an apparatus with only the first detector 60 for detecting reflected radiation, although more information is provided if there are both forward and reverse detectors and this makes it easier to work out the  
20 appropriate impedance adjustment to the impedance adjuster to minimise the amount reflected radiation.

Fig. 18 shows an alternative arrangement to that of Fig. 2 in which there are no mixers, but a phase  
25 comparator 65 is used instead. Like reference numerals indicate like parts as in Figs. 1 and 2. There is a forward coupler 250, a circulator 40, and impedance adjuster 50 and a reverse coupler 200 as described for Fig. 2. However forward directed microwave radiation  
30 from the forward coupler 250 is sent first to an frequency transformer 62 which acts as a local oscillator as in the arrangement of Fig. 17 and a magnitude sensor

(in this case a DC sensor) 61 and then from each of these to the phase comparator 65. The frequency transformer 62 transforms the microwave radiation to a lower frequency which can be handled by the phase comparator 65. The  
5 reverse coupler 200 is connected to a magnitude sensor 63 and a frequency transformer 63, which are each connected to the phase comparator in the same fashion for the corresponding parts 61 and 62 for the forward coupler 250. The phase comparator 65 takes the magnitude (power)  
10 information input from the magnitude sensor 61 and 63 and the transformed frequency signal from the frequency transformers 62 and 64 and from this works out the magnitudes and phases of the forward and reverse directed microwave radiation and sends this information to the  
15 controller 101.

It is important that the local oscillator 230 provides a signal having a different frequency to the frequency of the microwave radiation provided by the  
20 source 1. This is important in the Fig. 2 configuration, where mixers are used, because two different frequencies are needed for heterodyne detection. It is also important in the Fig. 18 configuration in which the frequency transformer 62 acts as a local oscillator  
25 because phase comparators are only able to handle satisfactorily frequencies much lower than the microwave frequencies produced by the source 1.

In the Fig. 2 example the local oscillator 230 is  
30 separate and independent from the source 1. However, it would be possible for the local oscillator to provide a signal derived from the source of microwave radiation 1. For example, as shown in Fig. 17, a coupler 22 could be

provided between the source of microwave radiation 1 and the pre-amplifying system 10 and configured to divert a portion of the microwave radiation to a frequency transformer 24. The frequency transformer 24, in effect  
5 acts as the local oscillator. It is connected to a mixer 220 and output a signal having a frequency different (usually much lower) from the frequency of the microwave radiation from the source 1 to the mixer 220. A reverse coupler 200 directs reflected microwave radiation to the  
10 mixer 220. The magnitude and phase of the reflected microwave radiation are determined by detecting device 240 connected to an output of the mixer 220. The other parts of the apparatus are not shown in Fig. 17 and would be the same as described previously in Figs. 1 and 2.

15

Fig. 16 shows an alternative embodiment of the apparatus in which like reference numerals indicate like parts to those described previously. There are two main differences. The first is that there is an additional  
20 detector indicated generally by reference numeral 33, positioned between the circulator 40 and the impedance adjuster 50. As will be appreciated by a person skilled in the art it could be positioned elsewhere e.g. between the circulator 40 and the dump load 210 or between the  
25 circulator 40 and the source 1. In the Fig. 16 embodiment the third detector 33 is configured to detect reflected microwave radiation, although in alternative embodiments it could be configured to detect forward directed microwave radiation. It comprises a reverse  
30 coupler 34, which is positioned between the circulator 40 and the impedance adjuster 50, a mixer 35 connected to the reverse coupler 34 and a detecting device 36. The

third detector 33 operates in the same fashion as the first and second detectors described previously. It provides further information which is helpful in determining the appropriate impedance adjustment to be  
5 made by the impedance adjuster 50 so as to minimise the amount of reflected microwave radiation.

The second main difference in the Fig. 16 embodiment is that a signal from the local oscillator 230 is mixed  
10 with a signal from the source of microwave radiation 1 in a mixer 45. It is the output signal from the mixer 45, rather than the signal directly from the local oscillator 230, which is input to the first, second and third detectors. The output of the mixer 45 is connected to a  
15 filter 46 which removes unwanted frequencies (usually the lower frequencies) produced in the mixer and passes the desired frequency to the inputs of the mixers 220, 260 and 35 of the first, second and third detectors. Fig. 16 also shows respective filters 221, 281 and 35a between  
20 the respective detectors' mixers 220, 260 and 35 and their respective detecting devices 240, 280 and 36.

The advantage of having a local oscillator signal which is derived from the source of microwave radiation  
25 (as in Fig. 17) or mixed with a signal from the source of microwave radiation (as in Fig. 16) is that the signal sent to the detectors then reflects any change in the frequency or phase of the source of microwave radiation.

### Impedance Adjuster and Controller

5       The impedance adjuster in this embodiment takes the form of a triple stub tuner 50, which is described in more detail later. In other embodiments a single, or double stub tuner or a semiconductor device for adjusting impedance could be used instead.

10       The impedance adjuster 50 is controlled by a controller 101 on the basis of the magnitude and phase detected by the detectors so as to minimise the amount of reflected microwave radiation. In this embodiment the controller 101 is an integrated circuit; in other  
15       embodiments it could be a computer with appropriate software.

20       The impedance adjuster 50 has an input connected, via the other components shown in Fig. 1 and 16, to the source of microwave radiation 1 and an output connected via one or more other components, to the probe 5. Usually the source of microwave radiation 1 will have a fixed real impedance and this will be matched with the impedance of the input of the impedance adjuster 50.  
25       Therefore the impedance of the input of the impedance adjuster 50 will in most cases be fixed. The complex impedance of the output of the impedance adjuster 50 is adjustable. By adjusting the complex impedance of the output of the impedance adjuster 50 it is possible to  
30       minimise the amount of radiation which is reflected from the tissue back through the probe 5. If the distance travelled by the microwave radiation between the output

of the impedance adjuster 50 and the distal end of the probe 5 is equal to a multiple of the wavelength of the microwave radiation divided by 2, then the complex impedance of the output of the impedance adjuster 50 can be matched directly to that of the tissue 6. If, however, it is not equal to such a multiple then the impedance of the components between the output of the impedance adjuster and the tissue/probe interface need to be taken into account (which is possible but which requires more computation by the controller 101).

There is also provided a user interface 110 allowing the operator to monitor the functioning of the apparatus, in particular the reflected magnitude and phase and optionally also the forward magnitude and phase, measured impedance of the load (tissue 6) to which the probe is applied, and amount of time for which the microwave radiation has been applied.

The user interface 110 also allows the operator to control the apparatus, adjust the power of microwaves by control of the amplifying system 2 through the controller 101 and start and stop the application of microwaves by the controller 101 or the power supply 120. This control may be affected through a foot switch or pedal 105.

#### Some Possible Applications of the Apparatus

The apparatus may be used to treat cancer by ablating a cancerous tissue. This may be performed by key-hole surgery whereby a small channel is cut into the surrounding tissue through which the probe can be

inserted until it reaches the cancerous tumour. The microwaves can then be used to ablate the tumour, the magnitude and phase of reflected microwaves being monitored as described above so that the impedance of the apparatus can be adjusted accordingly to minimise reflection of microwaves back into the probe. The microwaves may be emitted (generated by the source 1) when the probe is proximate the tumour or before. One possible method is to use the microwaves emitted from the probe 5 to cut a path through the surrounding tissue through which the probe can be inserted.

The source 1, amplifying system 2 and probe 5 will now be described in more detail.

#### Source of Microwave Radiation

In this embodiment the source of microwave radiation 1 is a voltage-controlled oscillator (VCO) whose frequency can be adjusted between 14GHz and 14.5GHz. In other embodiments different types of microwave source, e.g. a Dielectric Resonance Oscillator (DRO), or different frequency ranges could be used. VCO control and monitoring signals FoA and FoM are sent to and from the controller 101 (see Fig. 1) respectively.

It is preferred that the source of microwave radiation 1 is capable of outputting power at 0dBm and that its power level can remain constant with  $\pm 0.5$  dB over its output frequency band. The output frequency can be varied within the band (via the controller 101) and

this may be used to fine-tune the apparatus. For example there may be a specific frequency within the band whereby circuit resonances occur in the amplifying system 2 and maximum power can be achieved. It is also possible to  
5 sweep the frequency over the band to provide some instrument tuning, e.g. increase the frequency where the probe 5 and/or channelling means 4 are slightly too short for resonance or vice versa.

10 It is highly preferable that the source of microwave radiation is stable (i.e. provides a stable output). This assists the phase detection discussed above. One possible way of achieving stability is to use a phase locked source. A possible configuration for a phase  
15 locked source of microwave radiation is shown in Fig. 19. A VCO 1001 generates microwave radiation which is output to the rest of the apparatus via an amplifying system 2 as shown above in Fig. 1. A portion of the output signal from the VCO is coupled to a frequency transformer 1005  
20 which reduces the frequency of the signal and inputs it to a first input of a phase comparator 1015. A stable reference signal, such as a signal from a crystal oscillator, is input into a second input of the phase comparator. This is used to track any variation from the  
25 desired frequency of the microwave radiation  $f_0$ . The frequency provided by the stable reference is  $f_0/N$  and this can be stable because at lower frequencies very stable oscillators, e.g. crystal oscillators are available. The frequency transformer 1005 reduces the  
30 frequency output from the VCO by factor  $N$ . The phase comparator 1015 outputs the difference between the frequency and/or phase of the two input signals to an



amplifier and filter 1010 which feeds back to the input of the VCO to control and adjust its controlling voltage accordingly to correct any unwanted variation in the frequency and phase of the output signal.

5

Fig. 20 shows an alternative configuration for obtaining a stable output from the source of microwave radiation. A broadband source 1030 (which may be synthesised) is used to provide a wide range of microwave frequencies which are output to a narrow band filter 1040 which select a narrow band of frequencies (or one frequency) to be output. In this way a stable output of microwave radiation can be achieved.

#### 15 Amplifying System

The amplifying system 2 comprises a pre-amplifier stage or unit 10 and a power amplifier stage or unit 20.

20 One possible configuration of the power amplifier stage 20 is shown in Fig. 3. Microwave radiation is input to a preamp driver 300 from the output of the pre-amplifier stage 10. The preamp driver 300 outputs the radiation to a splitter 310 which divides the signal  
25 between four power amplifiers 320, 330, 340 and 350. The signal is amplified and output by each power amplifier and recombined by a combiner 360. Combiner 360 outputs the recombined signal to the detectors and impedance adjuster 3.

30

The choice of power amplifiers is determined by frequency output by the microwave radiation source 1. For

the 14 to 14.5 GHz range, GaAs FETs are particularly suitable. These preferably have a 1dB compression point of 43dBm (20w) over the bandwidth and a power gain of 6dB. TIM1414-20 from Toshiba Microwave Semiconductor Group may be used. When power amplifiers of this type are used the theoretical maximum output power level is 49dBm (80W).

In the Fig. 3 example the splitter 310 and combiner 360 are quarter wavelength microstrip devices.

Alternatively the amplifying system may have one or more microwave couplers for splitting the input signal between a plurality of power amplifiers and one or more microwave couplers for recombining the signals output from said power amplifiers. This has the advantage that if one of the power amplifiers fails then the mismatched energy can be diverted to a dump load connected to the isolated port of the coupler to which the failed power amplifier is connected and the other power amplifiers are not affected.

Fig. 4 is an example of an arrangement using microwave couplers. A pre-amp driver 400 is used as in the Fig. 3 example, but the arrangement for splitting the signal between the power amplifiers and recombining the amplified signals differs. The signal is split in two stages. The output of the pre-amplifier driver 400 is connected to a coupler that splits the signal between two outputs (ports 3 and 4 in Fig. 4). The signal from the first of these outputs is then directed to a first arm of the circuit 410a where it is split in two again by

another coupler 415 which directs the now twice split signal to first and second power amplifiers 420 and 430 and is recombined by a coupler 435. The coupler 435 outputs the signal to the input of a coupler 460.

5

The signal from the second port of the coupler 410 is directed to a second arm 410b of the circuit which has essentially the same construction as the first arm 410a above. Thus it has a coupler 417 for splitting the signal between a first port and a second port. The first port of said coupler is coupled to the input of a third power amplifier 440 and the second port to a fourth power amplifier 450. The outputs of said third and fourth power amplifiers 440, 450 are coupled to first and second input ports of a further coupler 455 for combining the input signals and the output of said further coupler 455 is connected to the coupler 460 for combining the signals from the two arms 10a, 10b of the circuit.

Although TM414-20 amplifiers are used as power amplifiers in Fig. 4, any suitable power amplifier can be used with appropriate modifications. Mitsubishi MEFK44 A4045 amplifiers may be advantageous.

The couplers 410, 415, 435, 417, 455 and 460 preferably split the power equally between their two outputs or combine equally from their two inputs, such couplers are known as 3dB 90° couplers.

As explained above, the advantage of the configuration of Fig. 4 is that if one of the power amplifiers fails then the mismatched energy is diverted

to a dump load connected to the isolated port of the coupler to which the failed power amplifier is connected. Thus the other power amplifiers are not affected.

5           Other configurations for the power amplifier stage will be apparent to a person skilled in the art.

          The amplifying system 2 has a power level controller. The power level controller is controlled by  
10 the controller 101 to give the desired level of output power. In the present embodiment the power level controller is in the pre-amplifying stage 10 of the amplifying system 2.

15           An example of one possible configuration for the pre-amplifier stage 10 is shown in Fig. 5. The output of the source of microwave radiation 1 is connected to the input of the pre-amplifier stage 10. The pre-amplifier stage 10 comprises a plurality of pre-amps 510, 520, 530  
20 and 540, which in the Fig. 5 example are connected in series. One of the pre-amps (in the instant example the second one 520) has a variable gain and so can be used to control the power level of microwaves output by the apparatus. The gain of the variable gain pre-amp 520 is  
25 controlled by the controller 101. Preferably the variable gain pre-amp is configured to operate only in its linear regions, but if a look-up table or similar software function is provided to convert low-level input power demands to a representative bias voltage then it may  
30 operate outside its linear region of operation.

An example of an alternative configuration is shown in Fig. 6. There are a plurality of pre-amps 610, 620, 630 and 640 as in the Fig. 5 example, but the power level controller is a pin diode attenuator 650 (which in turn is controlled by the controller 101). The pin diode attenuator 650 is placed between two of the pre-amps, which are connected in series. In the Fig. 6 example the pin diode attenuator 560 is placed between the first 610 and second 620 pre-amp. The pin diode attenuator 560 may be a reflective pin diode attenuator or a absorbative type attentuator.

The type and gain of the pre-amps are chosen according to the desired system requirements. Miniature Monolithic Integrated Circuit (MMICs) type pre-amps may be suitable. In one embodiment there are four pre-amps, the first having a gain of 7dB and the others 10dB each.

The source of microwave radiation 1, the pre-amplifier stage 2 and the power amplifier stage 3 may be combined as one unit, e.g. on a microstrip circuit board to make the apparatus compact.

#### Triple Stub Tuner and Stub Actuators

It is preferred that the impedance adjuster 50 is a stub tuner.

Fig. 7 shows a suitable triple stub tuner. The triple stub tuner 730 comprises a waveguide having two closed ends, an input 731, an output 732 and three tuning stubs 740, 750, 760. Each tuning stub 740, 750, 760 is

positioned in a respective aperture 741, 751, 761 in a wall of the waveguide and is moveable to vary the depth to which it extends into the waveguide. By varying the depth to which each stub extends into the waveguide it is possible to adjust the impedance of the impedance adjuster. In this way the impedance of the ablation apparatus 100, 200 can be matched to that of the tissue 6 to be ablated. Although the triple stub tuner shown in Fig. 7 is circular in cross-section (see Fig. 8), it would be possible to have one rectangular or square in cross-section.

In this embodiment an actuator (not shown in Fig. 7), such as a servomotor or piezoelectric device, controls the depth of each tuning stub 740, 750, 760. The actuator is controlled by the controller 101 on the basis of the magnitude and phase detected by the detectors and/or the user interface 110.

The apertures 741, 751 and 761 may be in different walls or the same wall of the waveguide as shown in Fig. 7.

The waveguide 730 of the triple stub tuner shown in Fig. 7 has an input side and an output side. The input side and the output side are D.C. (direct current) isolated from each other by a D.C. insulator 770. The insulator 770 allows passage of the frequencies of interest (those generated by the source of microwave radiation, e.g. 14-14.5GHz) but blocks D.C. Any suitable insulator may be used, Kapton tape or a thin sheet of low loss, high voltage breakdown dielectric material such as

PTFE or polypropylene are two possibilities. Preferably the insulation is good up to 6KV.

5 In the Fig. 7 example the waveguide 730 comprises two cylinders - one on the input side and one of the output side - which are fitted together one inside the other in a close fit and separated by the insulator 770. It is possible to separate the two cylinders which facilitates setting up and adjustment of the input and  
10 output probes 710 and 720.

The input and outputs 710 and 720 may conveniently be in the form of E-field probes extending into the waveguide. They may have type n-connectors for connection  
15 to the rest of the apparatus. H-field probes may also be used, as could SMA connectors.

The waveguide 730 is preferably cylindrical in cross-section as shown in Fig. 8 which is a cross-section  
20 along the line A-A of Fig. 7 and also shows the (laterally off-set) adjustable tuning stub 740.

In Fig. 7 the tuning stubs are placed one three eighths of a wavelength (of the microwave radiation  
25 generated by the source, or the average of its band) apart; in alternative embodiments they may be placed one eighth or five eighths wavelength apart - other suitable distances may be apparent to a person skilled in the art.

30 Fig. 21 shows an alternative embodiment of the apparatus in which like reference numerals indicate like parts to those described previously. Only the new

features will be described below, as the others have been described previously. A modulator 1100 and a filter 1120 are provided between the source of microwave radiation 1 and the amplifying system 2. The modulator 1100 is  
5 controlled by a modulating signal 1105 from the controller 101 to which it is connected. When it is in an ON state the modulator 1100 modulates the microwave radiation from the source 1 into pulses having a frequency in the range 10kHz to 500MHz inclusive. The  
10 modulator 1100 is flexible and capable of modulating to any frequency within this range, the frequency modulated being selected by the controller 101. The filter 1120 is connected to the output of the modulator 1100 and the input of the amplifying system 2. It is controlled by  
15 the controller 101. When the modulator 1100 is in an ON state the filter 1120 is controlled to filter out the higher microwave frequencies from the source 1, so that only a wave form having a frequency of the modulation pulses is passed. Thus, when the modulator 1100 is in  
20 its ON state radiation having a selected frequency in the range 10kHz to 500MHz is output to the rest of the apparatus and through the probe 5. Radiation of this frequency is particularly suitable for cutting. When the modulator 1100 is in an OFF state, the microwave  
25 radiation from the source 1 is not modulated and the filter 1120 passes the microwave radiation, so that microwave radiation is output to the rest of the apparatus and the probe 5. Microwave radiation is particularly effective for ablating cancerous tissue. It  
30 is preferred that the modulation frequency, when the modulator is in the ON state is a frequency in the range 500kHz to 30MHz, as these frequencies have been found



even more suitable for cutting of tissue because they are high enough that nerve stimulation is not produced but low enough that thermal margins are kept to a minimum.

5           Fig. 21 embodiment uses a 3 stub tuner as the impedance adjuster. A stub actuator 1130 is configured to control the stubs, so as to adjust the output impedance of the impedance adjuster, and is controlled by the controller 101 on the basis of the power and phase  
10 detected by the detectors 230, 250, 260, 280 and 200, 220, 240 and 270. Note that in Fig. 21 embodiment a separate local oscillators 230, 270 are used for the forward and reflected microwave radiation detectors.

15           A phase adjustor 1110 is provided between the impedance adjuster 50 and the probe 5. The phase adjuster 1110 is controllable by the controller 101 to make the effective distance between the output of the impedance adjuster 50 and the distal end 5a of the probe  
20 5 to be equal to a multiple of the wavelength of the microwave radiation produced by the source divided by two. As discussed previously this is advantageous for impedance matching and minimising the amount of reflected radiation.

25

As will be apparent to a person skilled in the art one or both of the modulator and the phase adjustor could be used in any one of the other embodiments described above.

30

Probes

The part of the ablation apparatus generally designated 100 in Fig. 1 may be used with many different types of probe 5. Accordingly the apparatus preferably has a probe detector that is capable of detecting the type of probe which is connected. The probe may have a device for sending an identifying signal to the probe detector. The probe detector may be part of the controller 101. The controller is configured to display probe type and procedural information relating to the detected probe, it may also be configured to vary the power level according to the probe type.

Various probes will now be described:

Fig. 9 shows a co-axial probe having a first conductor 900, a second conductor 910 and a dielectric 920 between the two. The first conductor 900 is of thin elongate form and is made of a highly conductive material such as silver or copper. The second conductor 920 is coaxial with the first and forms an outer conducting sheath. The dielectric is a low loss material for microwave frequencies. The characteristic impedance of the probe is determined by the ratio of the inner diameter of the second conductor 910 to the outer diameter of the first conductor 900. The dielectric 930 extends out of the conducting sheath 920 and the first conductor 900 extends further out of the dielectric and can be used to penetrate tissue 6. Fig. 10 is a cross-section along the line B-B of Fig. 9.

The probe of Fig. 9 has a plurality of baluns 930. Each balun is in the form of a third conductor surrounding a portion of the outer conductor 920. Each balun 930 is in conductive contact with the second  
5 conductor 910 at one end and insulated by air from second conductor for the rest of its length. Each balun has a length of one quarter of the wavelength or odd multiples thereof used by the apparatus. The baluns minimise the return current along the second conductor and thus help  
10 to minimise the risk of shock to the patient or the operator, and to reduce or eliminate the heating of healthy tissue.

Fig. 11 (a) shows a probe similar to that of Fig. 9, except that the first conductor 900 has a further piece of dielectric material 935 at its end (preferably the dielectric 935 is the same material as the dielectric 920). Only a portion 936 of the first conductor between the two pieces of dielectric material 920, 935 is  
20 exposed.

Fig. 11(b) is a close up view of the end of the probe of Fig. 9. Fig. 11 (c) is a close up view of the end of the probe of Fig. 11 (a). Fig. 11(d) shows a  
25 variant in which the first conductor has a dielectric 935 at its tip end, but the first piece of dielectric 920 does not extend out of the conductive sheath 910. Thus the portion of the first conductor between the sheath 910 and the second dielectric 935 is exposed. Fig. 11 (e)  
30 shows a variation in which the dielectric 920 does not extend out of the sheath 910, and the first conductor terminates in a tungsten needle 911 having a metal

ferrule 912 surrounding a portion proximate the end of the sheath 910.

Fig. 12 shows a coaxial probe inserted into tissue  
5 6. The same reference numerals indicate like parts as in Fig. 9. The second conductor 910 and baluns 930 are surrounded by a trocar, which is a tube inserted into the body that allows a probe or other device such as an endoscope to be inserted. Fig. 13 is a cross-section  
10 along the line C-C of Fig. 12.

Fig. 14 shows an alternative embodiment of the probe in which a balun is formed by spraying dielectric 932 between second and third conductors 910, 930.  
15 Dielectric - cast 235D from Cumming Corporation is a particularly suitable dielectric for this purpose. One or more baluns may be formed in this way. The length of the balun is one-quarter wavelength or odd multiples thereof.

20 In an alternative embodiment the baluns may be a pure dielectric baluns with no third conductor 930. Appropriate modifications will be apparent to a person skilled in the art.

25 Fig. 15 shows a rectangular waveguide probe having a depth of one half wavelength and a width of one wavelength. With this configuration the  $Te_{21}$  mode propagates. Microwaves are coupled into the ablation  
30 probe 6 via an E-field probe 2002 extending into the waveguide and having a type N or type K or SMA connector

2001. The waveguide aperture 2003 is filled (loaded) with a low loss dielectric.

5 Fig. 22 shows a cylindrical waveguide ablation probe 6, the central aperture 2003 of which is filled with a solid dielectric material. It has an E-field probe with an SMA, N or K type connector  $\lambda/4$  away from one of its ends. H-field probes could also be used.

10 In both Fig. 14 and Fig. 15 the waveguide housing (walls) are formed of copper, brass or aluminium and the input (E-field probe) is positioned one-quarter wavelength from one end of the waveguide.

15 Fig. 23 shows an elongate ablation probe having a ceramic tip 911 at its distal end. The tip is configured to deliver microwave radiation into tissue. The ceramic is a low loss microwave ceramic material having a relative permittivity ( $\epsilon_r$ ) of 6.5 at microwave  
20 frequencies.

Claims

1. A tissue ablation apparatus comprising:
  - a source of microwave radiation;
  - 5 a probe for directing the microwave radiation into the tissue to be ablated;
  - a local oscillator for producing a signal having a different frequency to said microwave radiation;
  - a first detector for detecting the magnitude and
  - 10 phase of microwave radiation reflected back through the probe towards the source, said first detector being connected to said local oscillator, and
  - an impedance adjuster having an adjustable complex impedance, between said source and said probe.
- 15 2. A tissue ablation apparatus for ablating tissue comprising:
  - a source of microwave radiation having a frequency;
  - a probe connected to said source, said probe being
  - 20 configured for directing said microwave radiation into said tissue to be ablated;
  - a local oscillator for producing a signal, having a frequency different to said frequency of said microwave radiation;
  - 25 a first detector for detecting the magnitude and phase of a reflected portion of said microwave radiation reflected back through said probe towards said source;
  - said first detector being configured to determine the magnitude and phase of said reflected portion of said
  - 30 microwave radiation on the basis of said signal produced by said local oscillator and said reflected radiation;
  - and

an impedance adjuster having an input connected to said source of microwave radiation and an output connected to said probe, said input and output having respective complex impedances, said complex impedance of said output being adjustable.

3. An apparatus according to claim 1 or claim 2 further comprising a second detector for detecting the magnitude and phase of forward directed microwave radiation directed from said source toward said probe, said second detector being connected to said local oscillator or a different local oscillator.

4. An apparatus according to claim 3 further comprising a third detector for detecting the magnitude and phase of either forward directed microwave radiation or reflected microwave radiation, said third detector being connected to said local oscillator or a different local oscillator.

5. An apparatus according to any one of the preceding claims wherein the or each detector comprises a mixer for mixing the signal from the local oscillator with the microwave radiation being detected by said detector.

6. An apparatus according to any one of claims 1 to 4 wherein the detector or detectors take the form of one or more power sensors and a phase comparator connected to said local oscillator.

7. An apparatus according to any one of the above claims wherein the or each local oscillator is separate from said source of microwave radiation.

8. An apparatus according to any one of the above claims wherein the or each local oscillator is connected to said source of microwave radiation and configured to produce a signal derived from said source, but having a different frequency to the frequency of said microwave radiation.
9. An apparatus according to any one of the above claims further comprising a controller for automatically adjusting said adjustable complex impedance of the impedance adjustor on the basis of the magnitude and phase of the radiation detected by said detector(s).
10. An apparatus according to claim 9 wherein said controller is configured to adjust said adjustable complex impedance dynamically in response to the variation in the magnitude and phase of the radiation detected by said detector(s).
11. An apparatus according to any one of the above claims where said probe is configured to penetrate biological tissue.
12. An apparatus according to any one of the above claims and having a separator for separating reflected microwave radiation from forward directed microwave radiation being directed towards the probe.
13. An apparatus according to any one of the above claims wherein the impedance adjuster is a stub tuner.



14. An apparatus according to any one of the above claims wherein there is a coupler for directing some of the reflected radiation to the first detector.

5 15. An apparatus according to any one of the above claims wherein the probe is coaxial.

16. An apparatus according to any one of the above claims wherein the probe is a waveguide.

10

17. An apparatus according to any one of the above claims wherein the probe has an outer diameter of less than 1mm.

15 18. A microwave tissue ablation apparatus according to any one of claims 1 to 17 wherein the source of microwave radiation produces radiation of wavelength  $\lambda$ , and a radiation channelling means for conveying microwave radiation connects said impedance adjuster and said  
20 probe, said channelling means having an adjustable length whereby the combined length of said channelling means and said probe can be adjusted to be equal to a multiple of  $\lambda/2$ .

25 19. A method of ablating tissue comprising the steps of:

using a source of microwave radiation to provide microwave radiation;

30 placing a probe in contact with or inserting a probe into biological tissue;

directing said microwave radiation through said probe into the tissue to ablate the tissue;

detecting the magnitude and phase of microwave radiation reflected back through the probe by using a first detector and a local oscillator, and

5 adjusting the complex impedance of an impedance adjustor between said source and said probe on the basis of the magnitude and phase of the microwave radiation detected by said first detector.

10 20. A method of ablating tissue comprising the steps of:

using a source of microwave radiation to provide microwave radiation having a frequency;

placing a probe in contact with or inserting a probe into biological tissue;

15 directing said microwave radiation from said source through an impedance adjuster and then through said probe into said tissue to ablate the tissue; said impedance adjustor having an input connected to said source and an output connected to said probe, said input and said  
20 output having respective complex impedances;

detecting the magnitude and phase of reflected microwave radiation reflected back through the probe by using a first detector and a local oscillator; said local oscillator generating a signal having a frequency  
25 different to said frequency of said microwave radiation, said first detector using said local oscillator signal in combination with the reflected radiation or a signal derived from said reflected radiation to determine the magnitude and phase of said reflected radiation;

30 and adjusting said complex impedance of said output of said impedance adjustor on the basis of said magnitude and phase of said reflected microwave radiation detected

by said first detector, so as to minimise the amount of microwave radiation which is reflected back through said probe.

5       21. A method according to claim 19 or 20 wherein the probe is inserted into the tissue so that an end of the probe is proximate to or inside a cancerous tumour in the tissue and microwave radiation is then passed through the probe to ablate said cancerous tumour.

10

22. A method according to claim 21 wherein the microwave radiation is used to cut a path in the tissue so that the probe can be inserted near to or into said tumour.

15

23. A method according to claim 20 wherein the magnitude and phase of forward directed microwave radiation directed toward said probe from said source of microwave radiation is detected by using a second detector and said local oscillator or a different local oscillator and said adjustable complex impedance of said impedance adjuster is adjusted based on the magnitude and phases detected by said first and second detectors.

20

25       24. A method according to claim 23 wherein a third detector is used to detect the magnitude and phase of either forward directed or reflected radiation and said adjustable complex impedance of said impedance adjuster is adjusted on the basis of information provided by said first, second and third detectors.

30

25. A method according to any one of claims 19, 20, 23 or 24 wherein said adjustable complex impedance of said impedance adjuster is adjusted automatically by a control means on the basis of said magnitude and phase detected  
5 by said detector(s) so as to minimise the amount of microwave radiation reflected back through the probe.

26. A method according to claim 25 wherein the impedance adjustment is carried out dynamically as the  
10 detected magnitude and phase varies.

27. An elongate microwave probe for delivering microwave radiation into tissue to be ablated, said probe having an elongate portion and a tip at one end of said  
15 elongate portion, said tip being formed of a ceramic material and being configured to deliver microwave radiation into tissue.

20 28. A coaxial tissue ablation probe having an inner conductor, a dielectric surrounding said inner conductor, a conducting sheath surrounding said dielectric and one or more baluns on said sheath, the or each balun comprising a spray-on dielectric.

25 29. A probe according to claim 28 wherein the or each balun further comprises an outer conductor surrounding said spray-on dielectric.

30 30. A probe according to claim 28 or 29 wherein said probe is designed for use with microwave radiation of wavelength  $\lambda$  and the or each said balun has a length in

the direction of the axis of said probe of  $\lambda/4$  or odd multiples thereof.

5 31. A method of making a balun for a coaxial tissue ablation probe comprising the steps of spraying or otherwise placing a liquid or powder dielectric onto an outer surface of an outer conducting sheath of a coaxial probe, and if said dielectric is liquid allowing the liquid to solidify, to form the balun.

10

32. A method according to claim 31 comprising the further step of and placing an outer conductor around said dielectric.

15 33. A method according to claim 32 wherein said probe is designed for use with a microwave radiation of wavelength  $\lambda$  and the balun has a length in the direction of the axis of said probe of  $\lambda/4$  or odd multiples thereof.

20

34. A surgical apparatus comprising:

a source of microwave radiation of a first frequency suitable for ablating tissue;

25 a probe for directing microwave radiation from the source into tissue to be ablated;

a modulator having an OFF state in which it does not modulate said microwave radiation from the source and an ON state in which it modulates microwave radiation from the source in pulses having a second frequency less than said first frequency; said second frequency being suitable for cutting tissue.

30

35. An apparatus according to claim 29 wherein the apparatus further comprises a low pass filter between said modulator and said probe; said low pass filter  
5 having a first state in which it lets said first frequency pass and a second state in which it passes said second frequency, but filters out said first frequency.
36. An apparatus according to claim 34 wherein said  
10 modulator is capable of varying said second frequency.
37. An apparatus according to claim 36 wherein said modulator is capable of varying said second frequency and said low pass filter is capable of varying its pass band  
15 in its second state.
38. An apparatus according to any one of claims 34 to 37 wherein said first frequency is 5GHz or higher.
- 20 39. An apparatus according to any one of claim 34 to 38 wherein said second frequency is a frequency in the range 10kHz to 500MHz.

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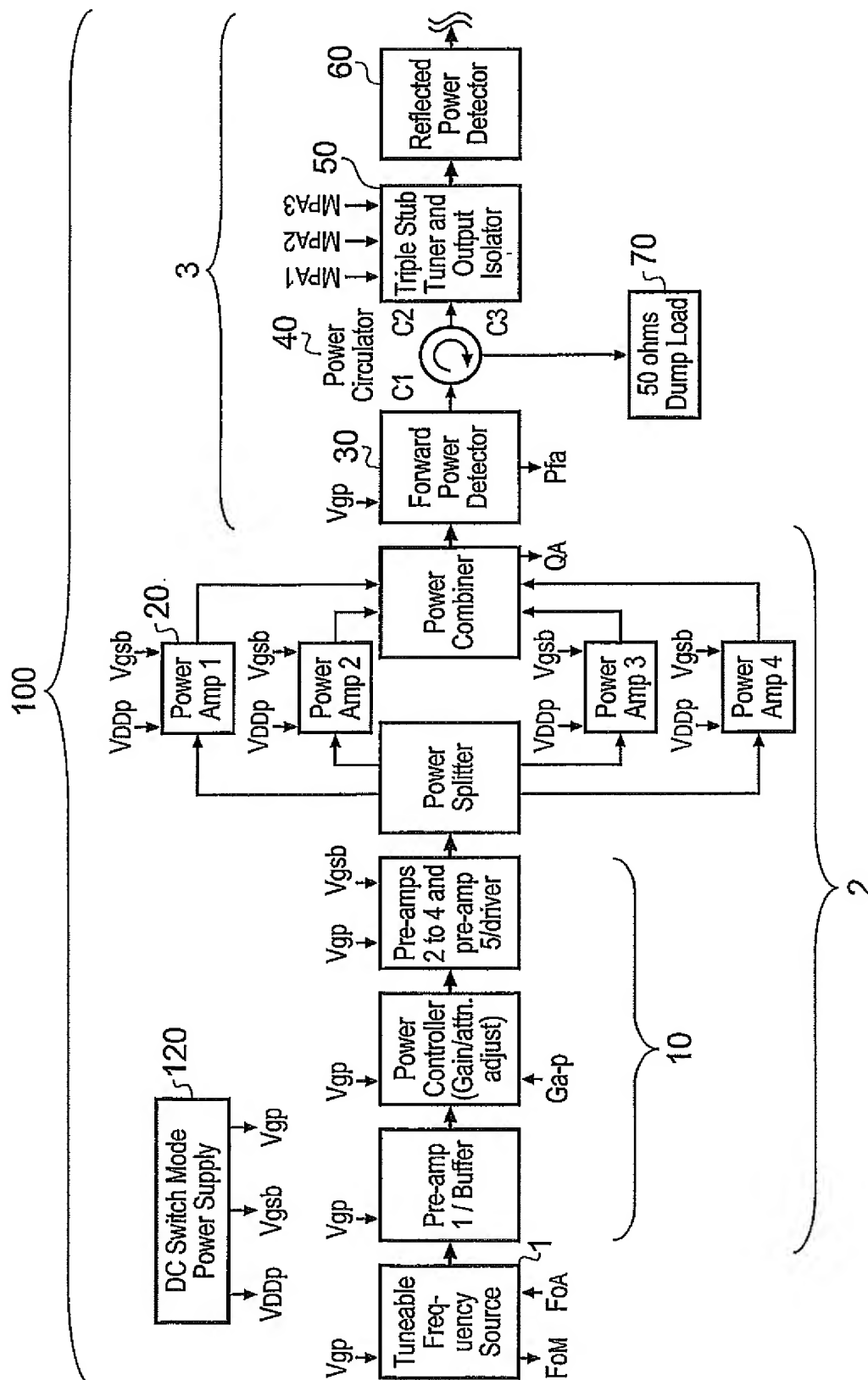


Fig. 1 (continued on page 2/14)

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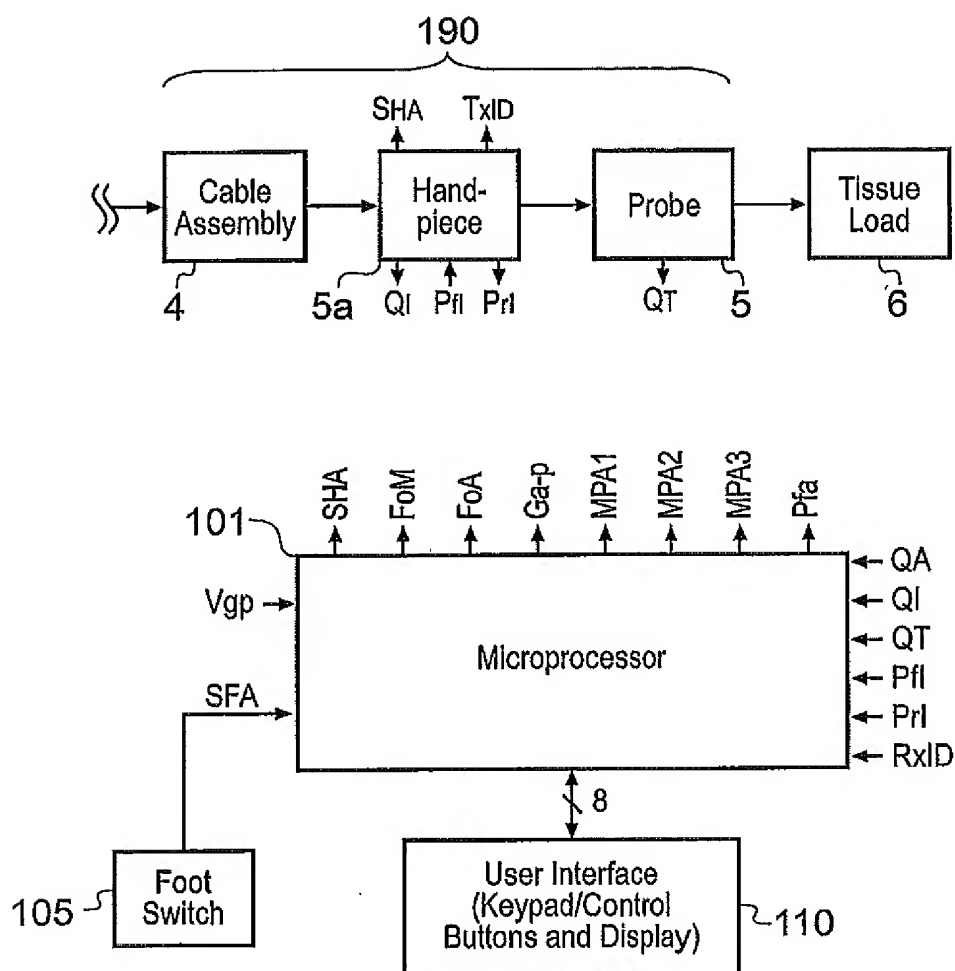


Fig. 1 (continued from page 1/14)



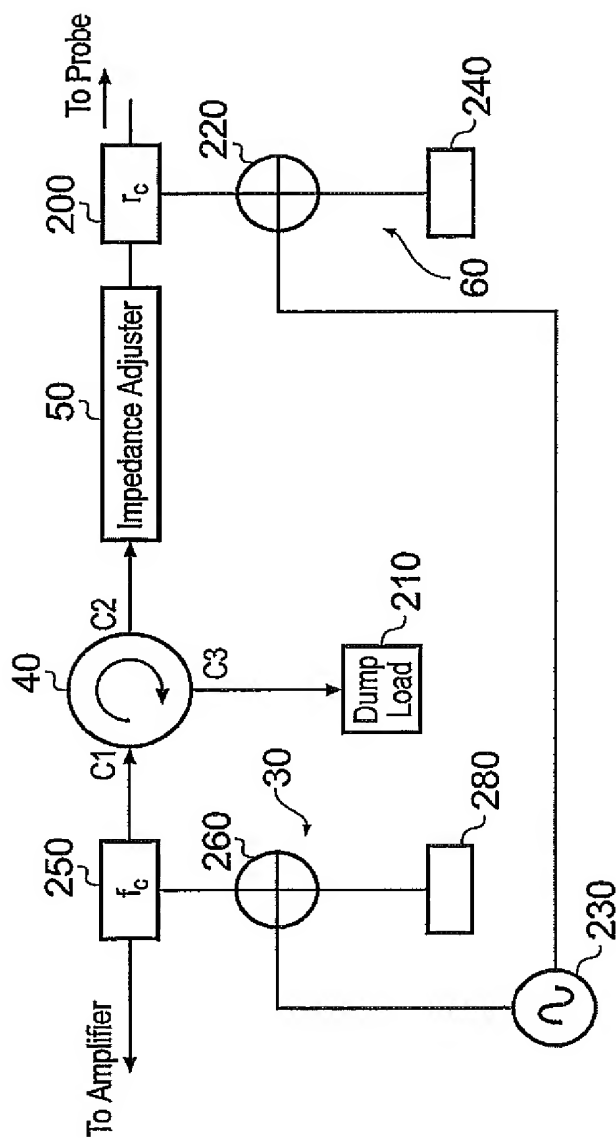


Fig. 2

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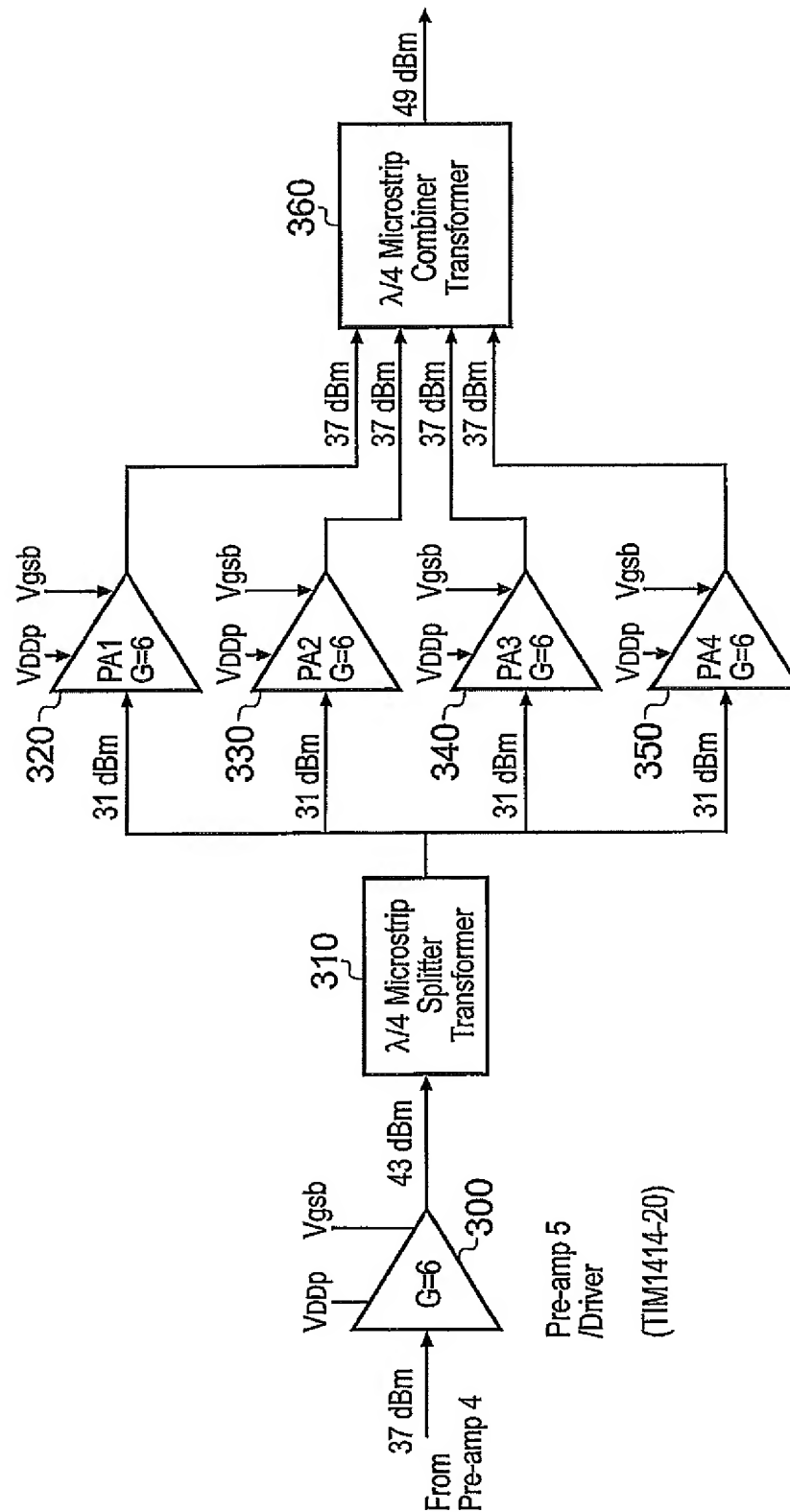


Fig. 3

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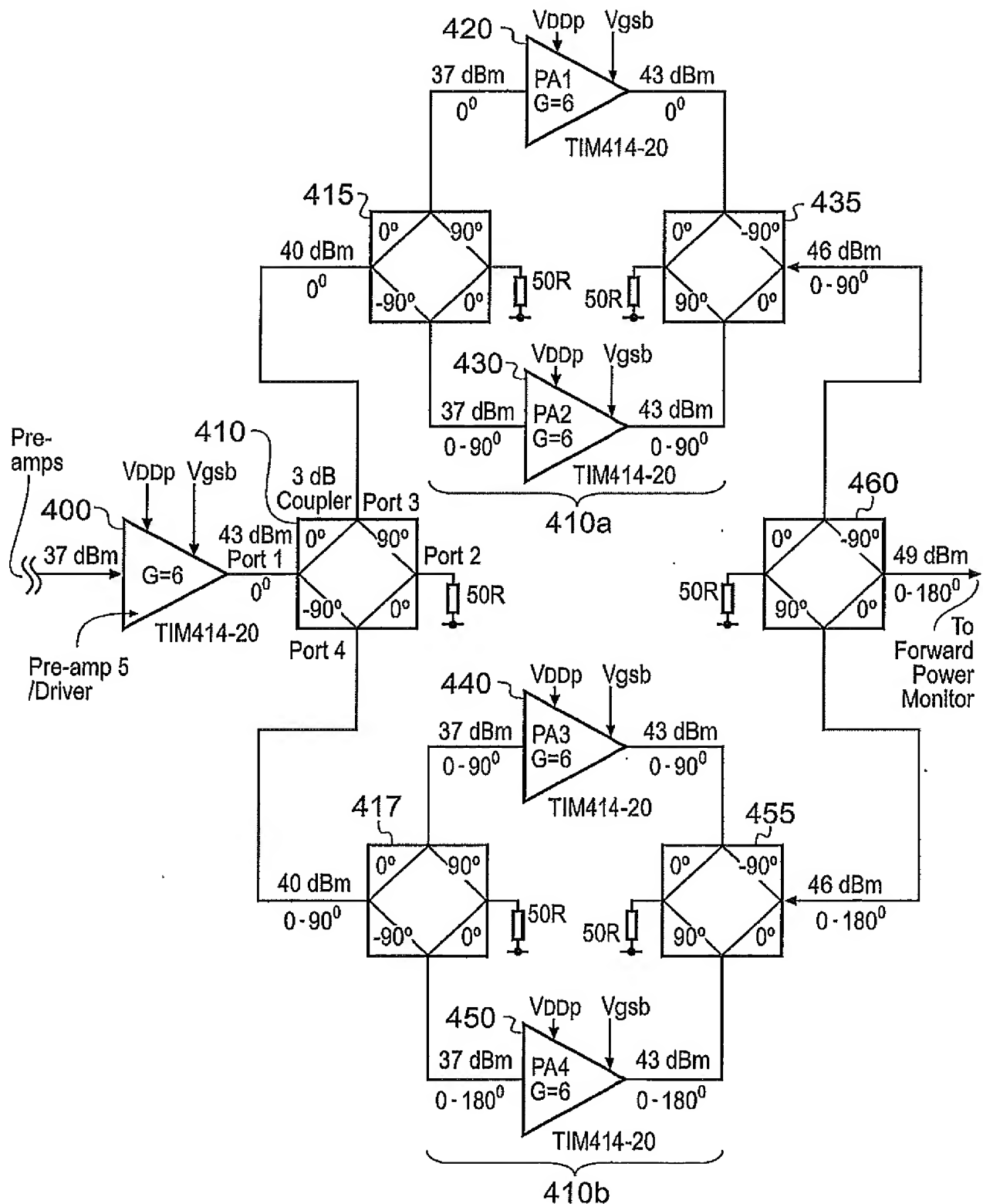


Fig. 4

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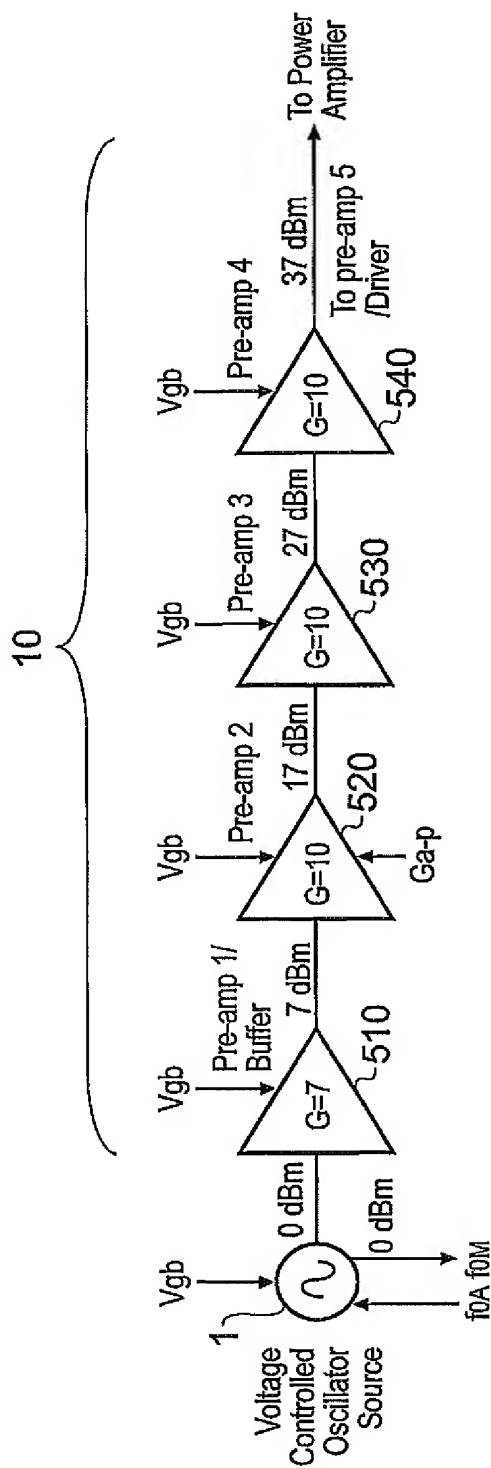


Fig. 5

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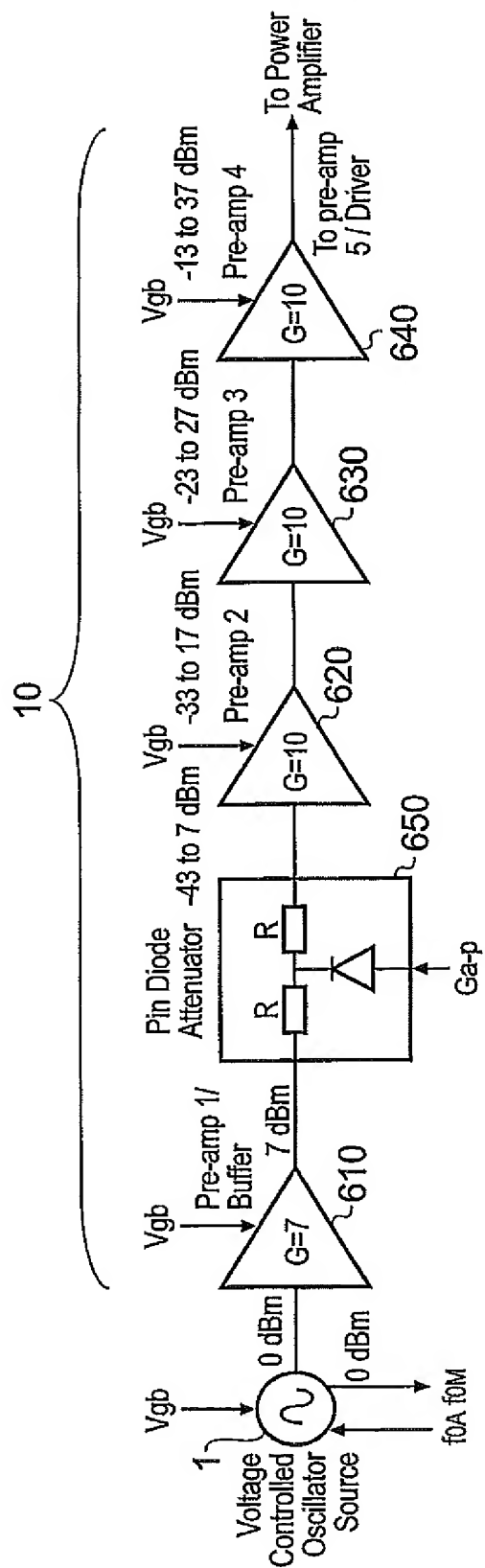


Fig. 6

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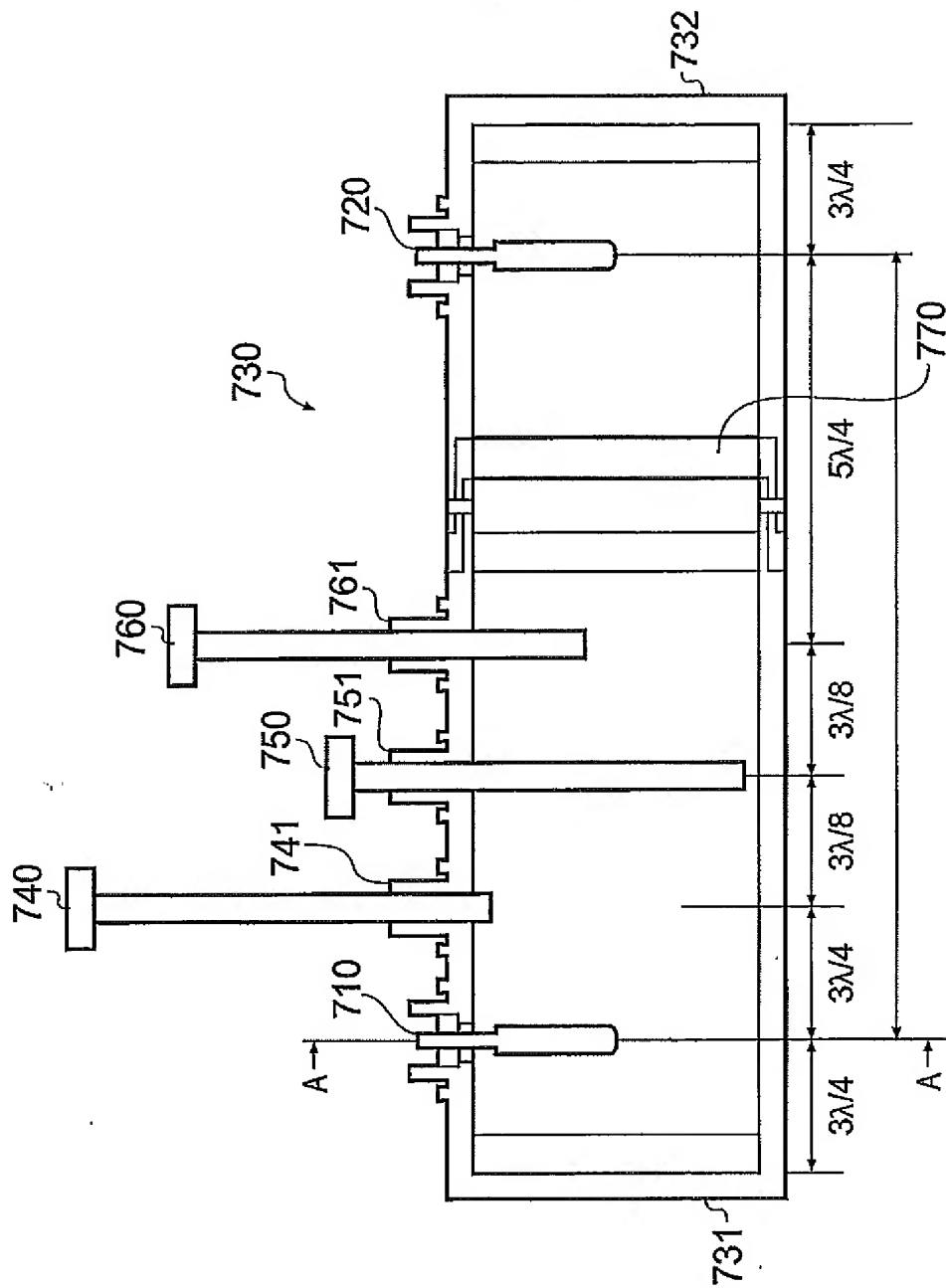
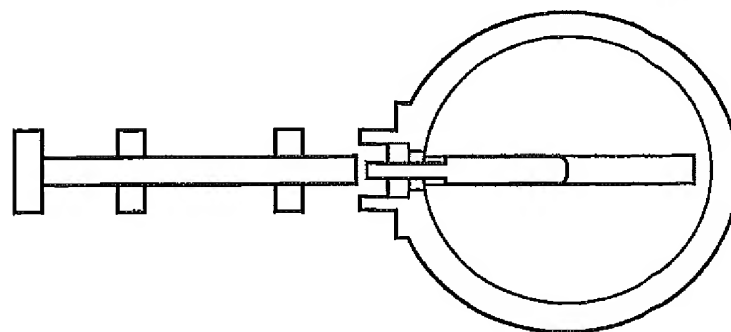


Fig. 7



Section A - A

Fig. 8

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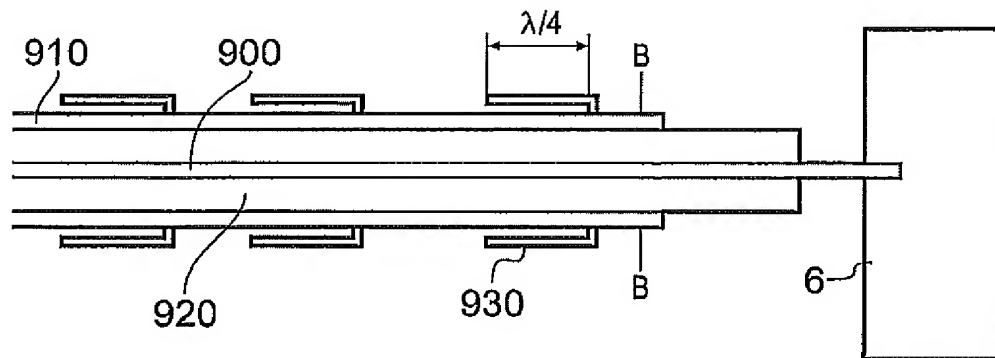


Fig. 9

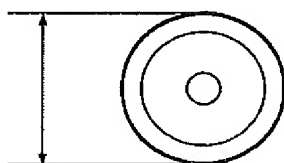


Fig. 10

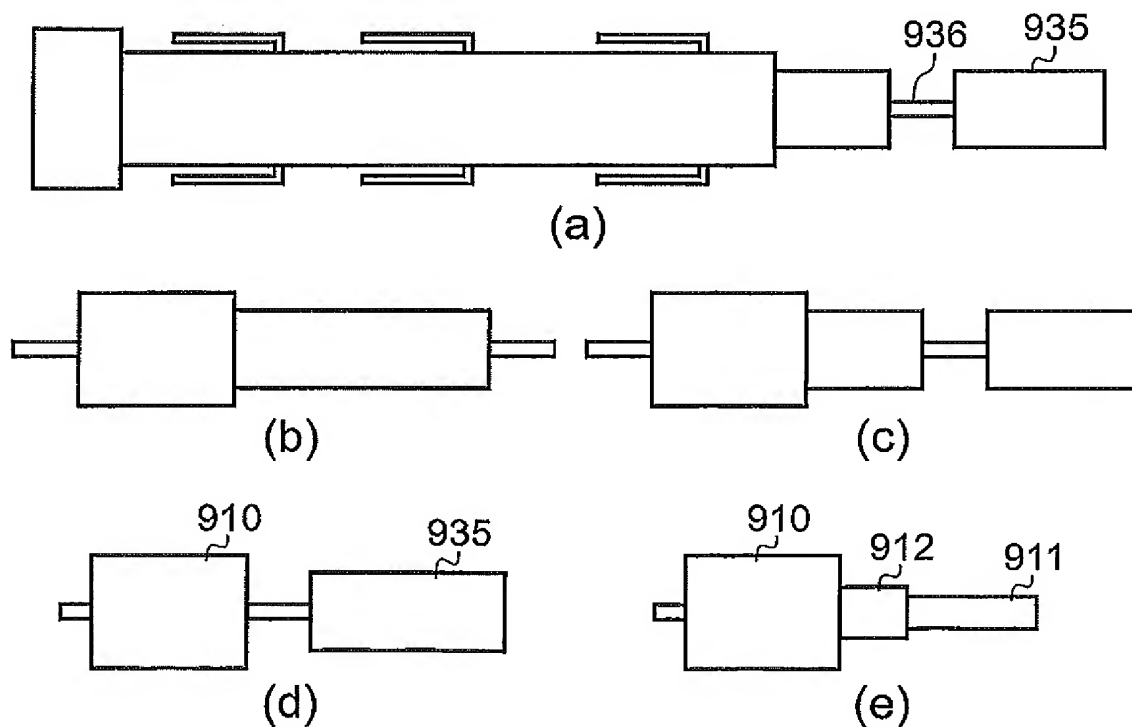


Fig. 11

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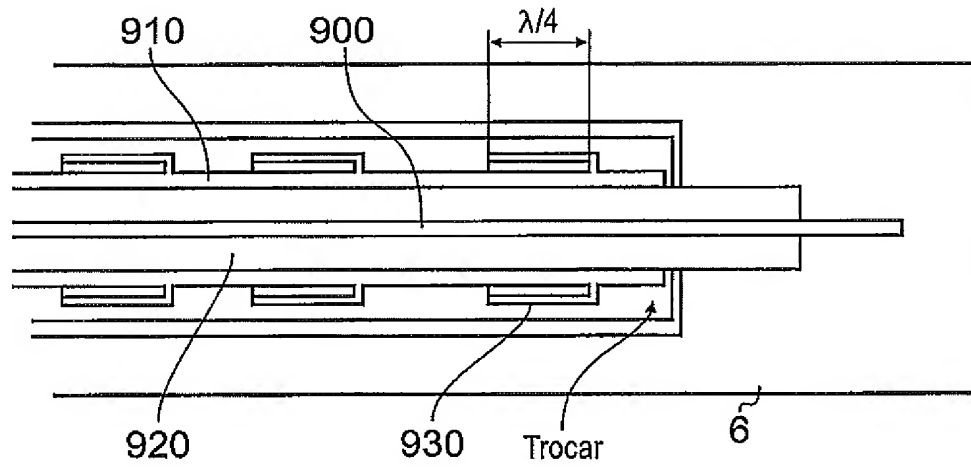


Fig. 12

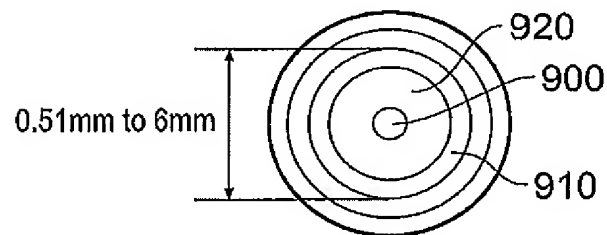


Fig. 13

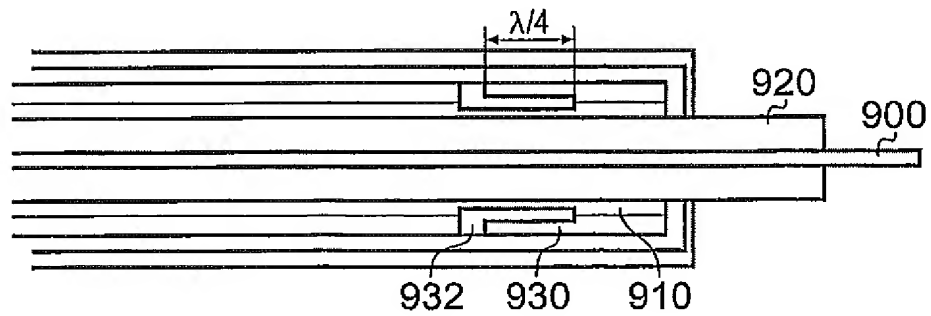


Fig. 14



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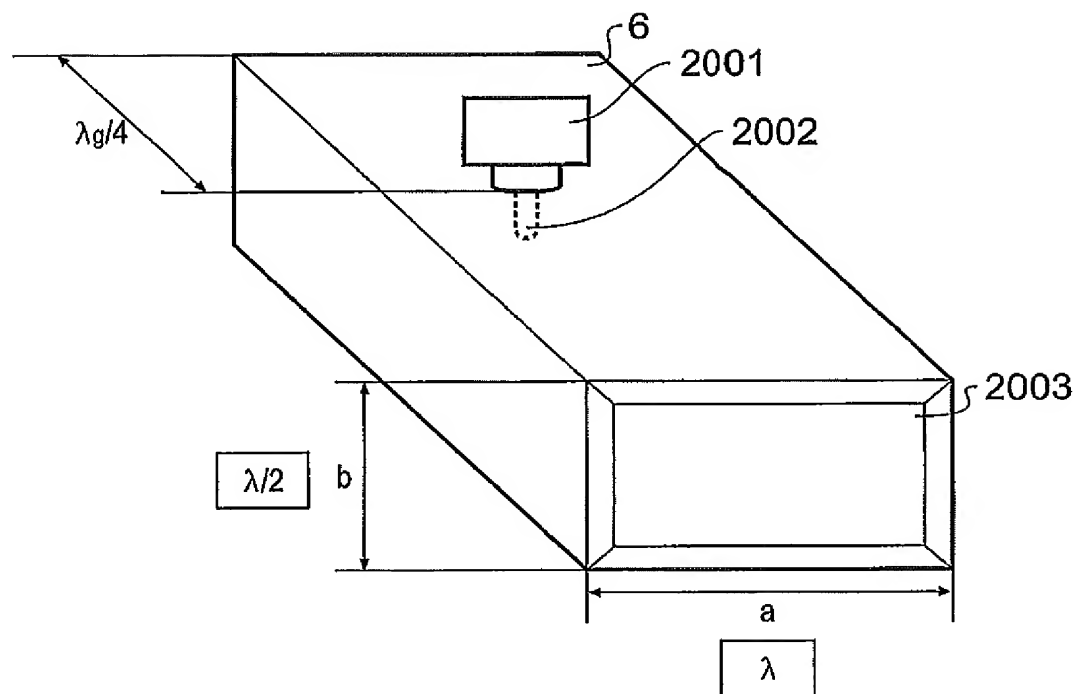


Fig. 15

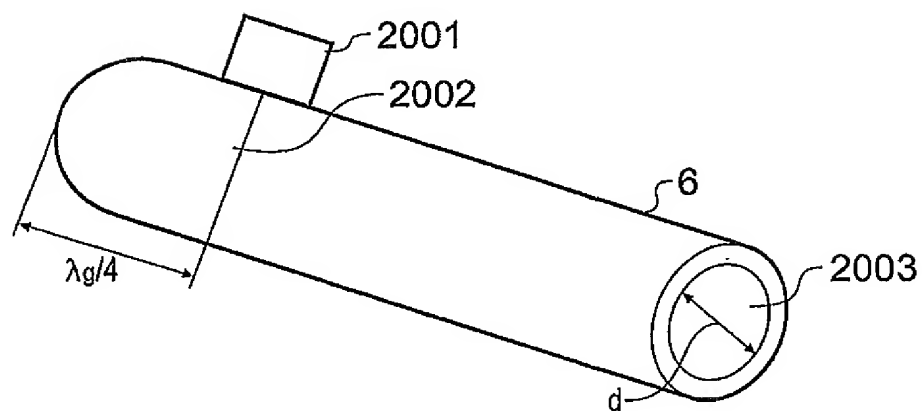


Fig. 22

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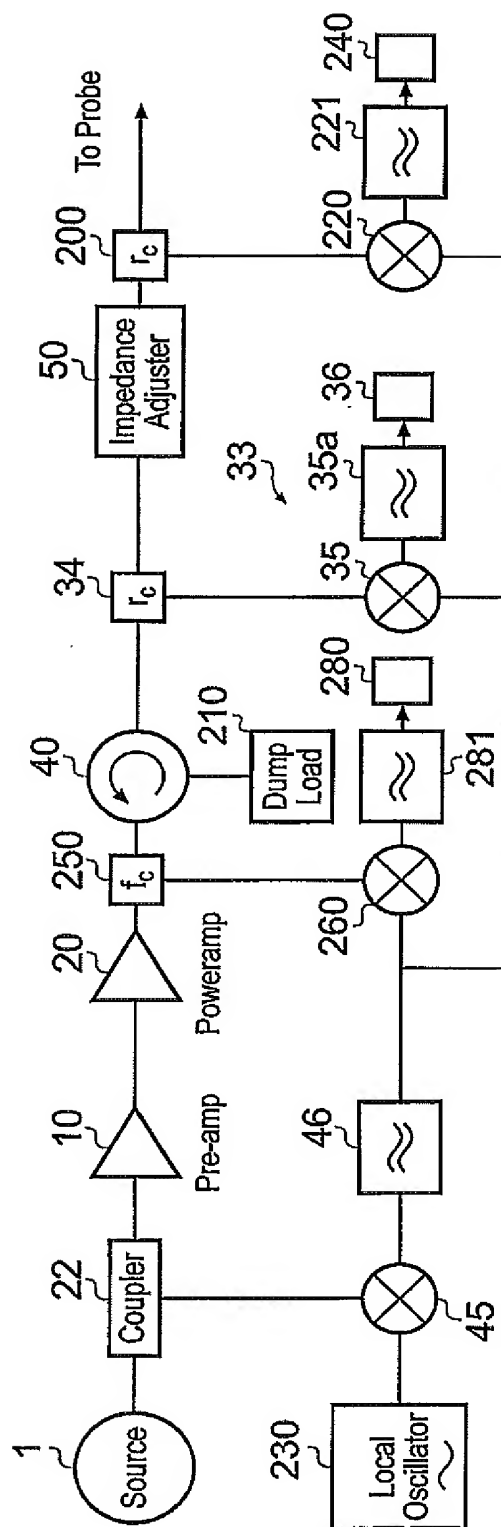


Fig. 16

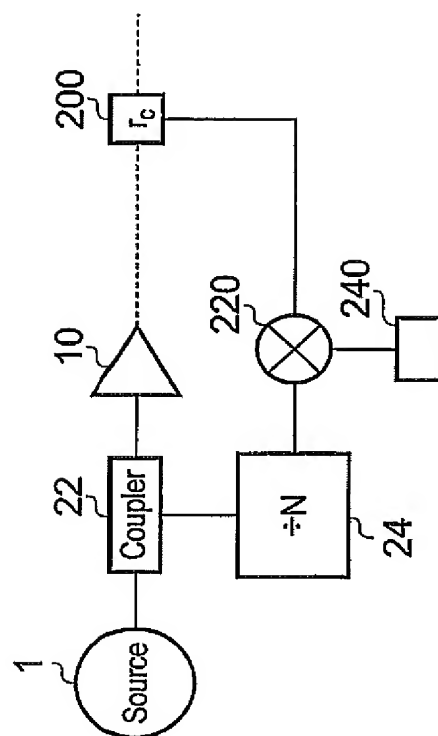


Fig. 17

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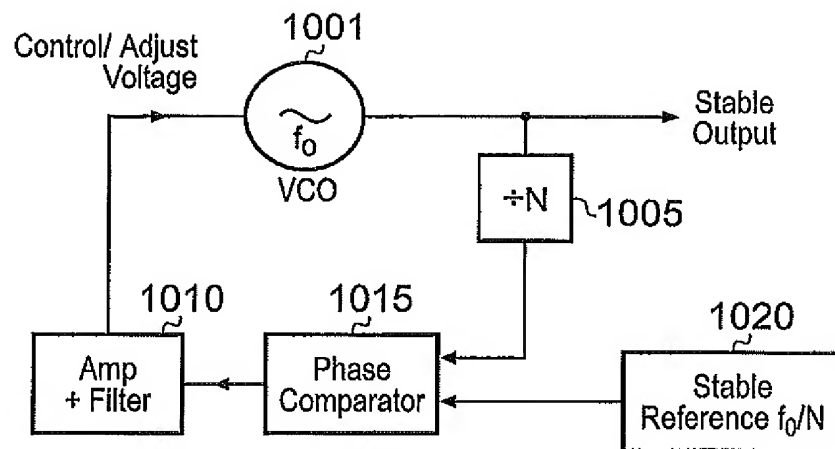


Fig. 19

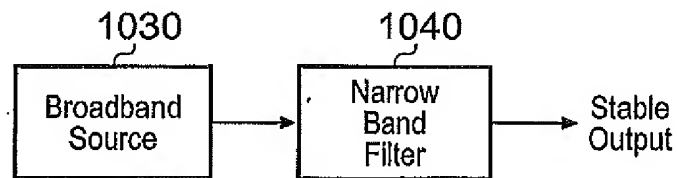


Fig. 20

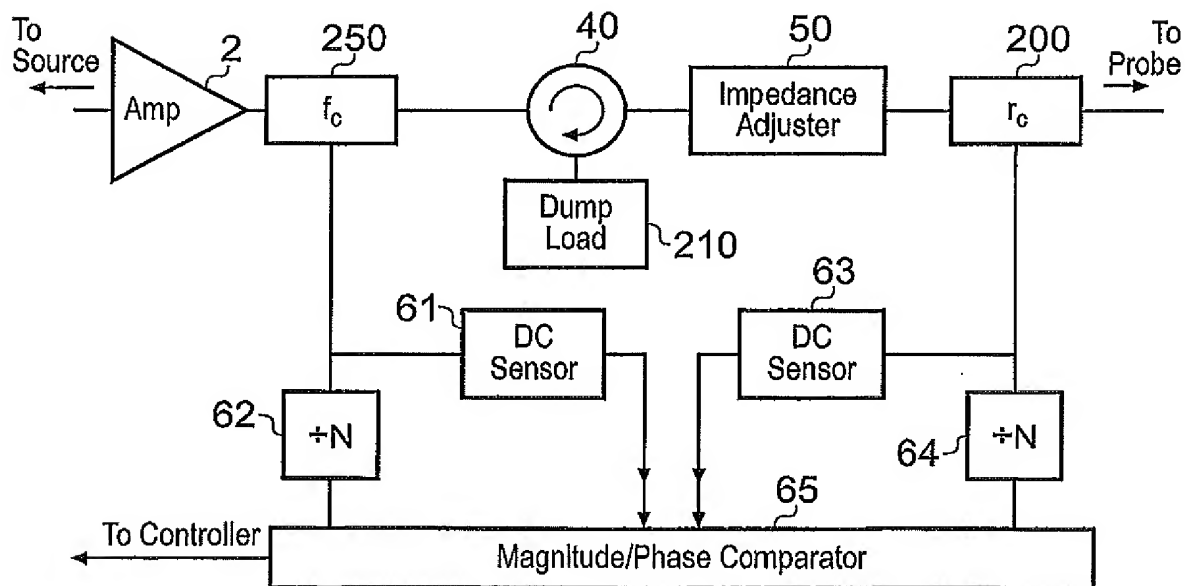


Fig. 18

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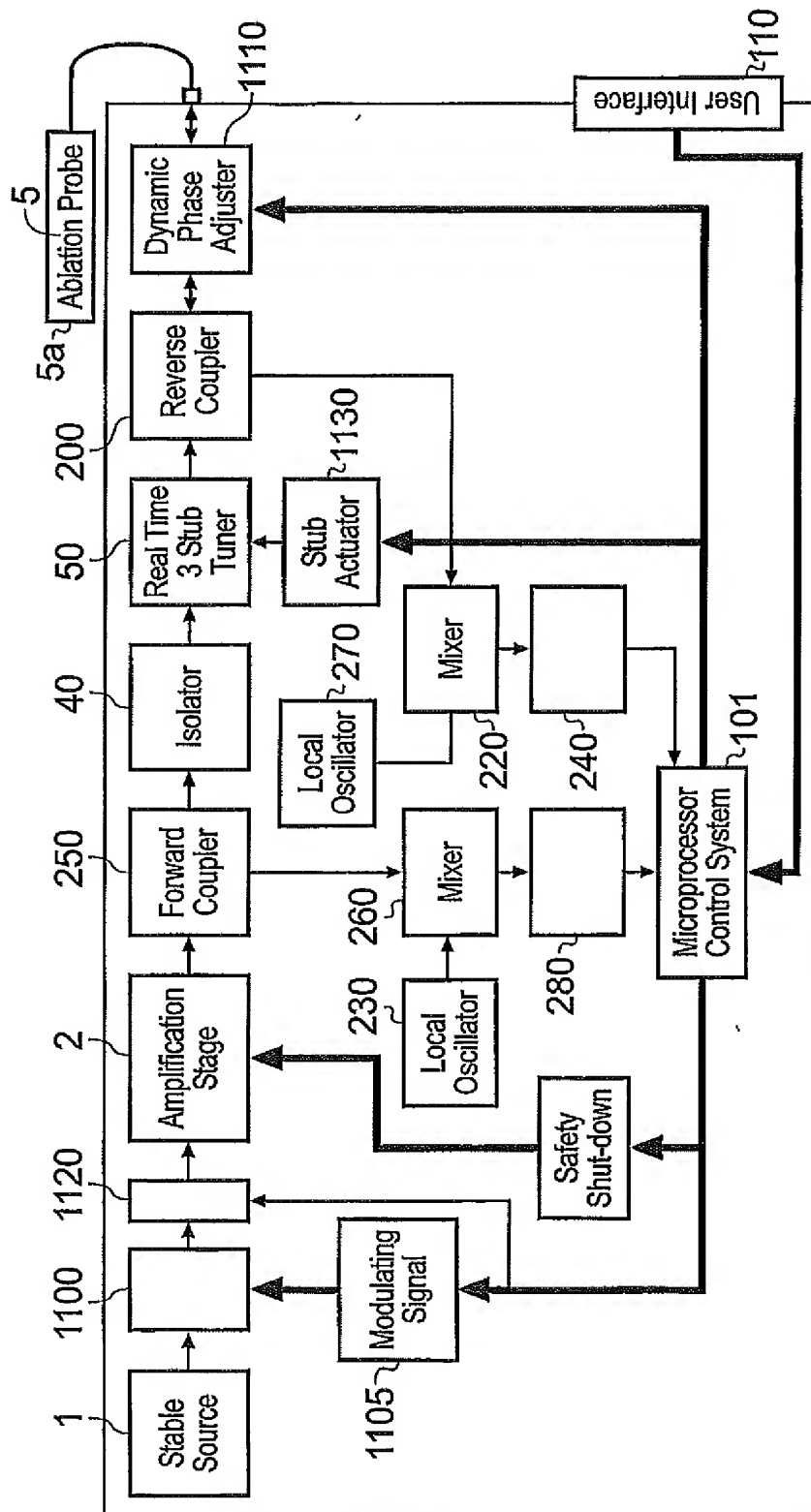


Fig. 21

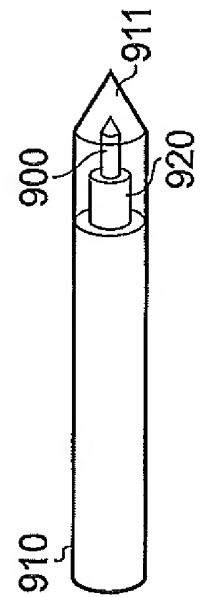


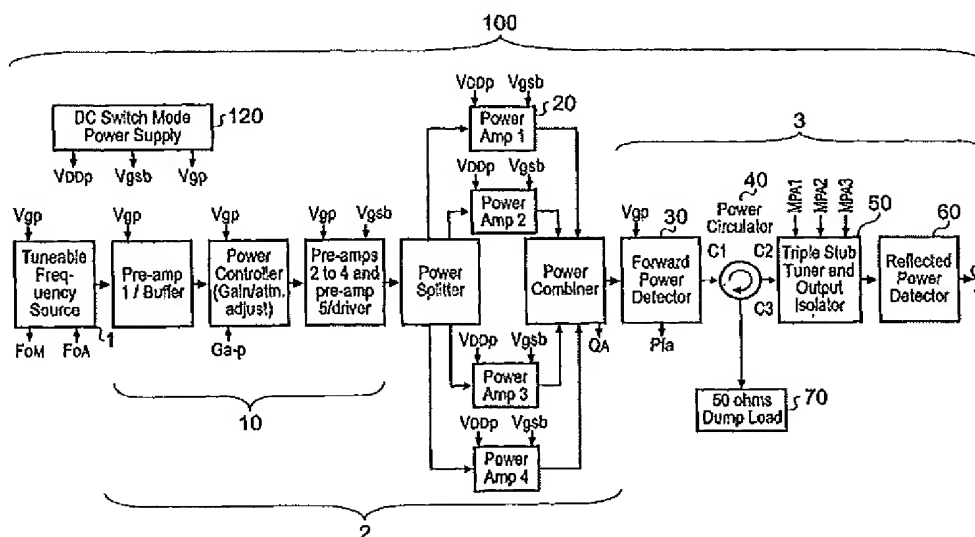
Fig. 23



(10) International Publication Number  
**WO 2004/047659 A3**

[Continued on next page]

**(54) Title:** TISSUE ABLATION APPARATUS AND METHOD OF ABLATING TISSUE



**(57) Abstract:** An apparatus and method for ablating tissue is disclosed. The apparatus comprises a source of microwave radiation (1), a probe (5) for directing the microwave radiation into tissue, one or more detectors for detecting the power and phase of the microwave radiation and an impedance adjuster (50) for adjusting impedance so as to minimize the amount of microwave radiation which reflected back through the probe. The detector or detectors use a local oscillator (230) to derive the phase information. A modulator for modulating the microwave radiation to a cutting frequency is also disclosed.



— *before the expiration of the time limit for amending the claims and to be republished in the event of receipt of amendments*

*For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.*

(88) Date of publication of the international search report:  
29 July 2004

## INTERNATIONAL SEARCH REPORT

Application No  
PCT/GB 03/05166A. CLASSIFICATION OF SUBJECT MATTER  
IPC 7 A61B18/14

According to International Patent Classification (IPC) or to both national classification and IPC

## B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)  
IPC 7 A61B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the International search (name of data base and, where practical, search terms used)

EPO-Internal, WPI Data, PAJ

## C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 5 957 969 A (GRUNDY DAVID ALAN ET AL) 28 September 1999 (1999-09-28) column 2, line 11 -column 15, line 3; figures 1,6-12 ---	1-18
X	US 5 693 082 A (GRUNDY DAVID ALAN ET AL) 2 December 1997 (1997-12-02) column 2, line 7 -column 14, line 67; figures 1,6-12 ---	1-18
X	US 5 364 392 A (WARNER GLEN G ET AL) 15 November 1994 (1994-11-15) column 2, line 30 -column 8, line 40; figures 1,6,7 --- -/--	1-18

☒ Further documents are listed in the continuation of box C.☒ Patent family members are listed in annex.

## \* Special categories of cited documents:

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Date of the actual completion of the international search

27 May 2004

Date of mailing of the international search report

11.06.2004

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## INTERNATIONAL SEARCH REPORT

 Application No  
 PCT/GB 03/05166

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# INTERNATIONAL SEARCH REPORT

application No.  
PCT/GB 03/05166

## Box I Observations where certain claims were found unsearchable (Continuation of item 1 of first sheet)

This International Search Report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☒ Claims Nos.: 19-26  
because they relate to subject matter not required to be searched by this Authority, namely:  
Rule 39.1(iv) PCT - Method for treatment of the human or animal body by surgery
2. ☐ Claims Nos.:  
because they relate to parts of the International Application that do not comply with the prescribed requirements to such an extent that no meaningful International Search can be carried out, specifically:
3. ☐ Claims Nos.:  
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

## Box II Observations where unity of invention is lacking (Continuation of item 2 of first sheet)

This International Searching Authority found multiple inventions in this International application, as follows:

see additional sheet

1. ☐ As all required additional search fees were timely paid by the applicant, this International Search Report covers all searchable claims.
2. ☐ As all searchable claims could be searched without effort justifying an additional fee, this Authority did not invite payment of any additional fee.
3. ☒ As only some of the required additional search fees were timely paid by the applicant, this International Search Report covers only those claims for which fees were paid, specifically claims Nos.:  
1-18, 34, 36-39
4. ☐ No required additional search fees were timely paid by the applicant. Consequently, this International Search Report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

### Remark on Protest

☐ The additional search fees were accompanied by the applicant's protest.

☒ No protest accompanied the payment of additional search fees.

**FURTHER INFORMATION CONTINUED FROM PCT/ISA/ 210**

This International Searching Authority found multiple (groups of) inventions in this international application, as follows:

1. Claims: 1-18

Tunable tissue ablation apparatus

2. Claim : 27

Probe with ceramic tip

3. Claims: 28-33,35,38,39

Coaxial probe and method of making a balun therefor

4. Claims: 34,36-39

Surgical apparatus with modulator

## INTERNATIONAL SEARCH REPORT

Information on patent family members

Application No

PCT/GB 03/05166

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